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PREFACE

Beginning 1931, the dates of issue of the Quarterly TRANSACTIONS have been advanced three months, Part I being dated March, Part II June, Part III September, and Part IV December. This volume is the fourth Quarterly for 1931 and contains the papers and discussions presented at the Summer Convention, Asheville, N. C., and the complete reports of the Technical Committees for the current year.

Following the established practise, the last Quarterly of each year contains a complete annual subject and authors' index which in this volume covers the contents of the four 1931 Quarterlies.

Communication in the Western Division of the Niagara Hudson System

BY EDWIN S. BUNDY[1]

Member, A. I. E. E.

EXTENSIVE interconnection of electric generating and transmitting systems has brought the problem of rapid, dependable communication to the fore. Present day systems cover such large areas that the communication lines have become almost as important as the power lines themselves.

Men operating these systems must have some means of immediate communication with several points on the system. More than that, the system of communication must be highly reliable and as safe from the destructive forces of nature as it can be made, because it is usually most needed when power system operation is upset by storms.

The area covered by the Western division of the Niagara Hudson System and the location of the various generating and switching points are given below:

The Niagara Hudson System spans New York State from the Pennsylvania border, near Jamestown, to the Massachusetts border, near Albany, with a branch of the lines extending northward to the International boundary between New York and Quebec. The western division of this system includes all that part west of Lyons. This area is shown graphically on the copy of the system map in Fig. 1.

Main generating stations of the western division are located at Niagara Falls and Buffalo, but power is also available from plants on the Adirondack streams and in the Mohawk and Hudson river valleys. Through interconnections, power may also be secured from plants on the Canadian side of the Niagara River and from an adjoining system in Pennsylvania.

Main switching stations of the western division are located at Buffalo, Niagara Falls, Gardenville, Lockport, Mortimer, Jamestown and Olean. These points are clearly designated on the system map.

In the economical operation of a large system such as this, which includes both steam and hydroelectric plants, rapid and dependable communication between the division load supervisor's office in Buffalo and the various generating and switching points, as well as between those points, is vital. Recognizing this fact, the system now in use was devised and is believed to fulfill all requirements.

Prior to the organization into one system of the various companies comprising the western division, each company arranged for its own communication facilities. In some cases this involved the building of telephone circuits by the power company, in some cases the leasing of circuits from the telephone company and in some cases merely the use of telephone toll service. It was only natural that different companies should have different ideas on the subject.

Following the grouping of the companies into the Niagara Hudson System, it immediately became apparent that communication facilities should be rearranged and revised to meet the needs of the coordinated system. Greater flexibility was needed. Engineers of the telephone company were called in to make a survey and a report. Upon the completion of this survey, they submitted a report covering the complete communication needs of the western division. This report is divided into three sections: inter-office communication in the Electric Building at Buffalo, communication between substations, extensions in the Service Building and lines to Huntley Station. These are all extensions from the private branch exchange and comprise more than 700 miles of extensions; inter-department communication at Huntley Station, lines connecting Terminal Houses A, B, C and D in Buffalo, and lines to Niagara Falls and the Tonawandas; communication channels to main switching and generating stations and other strategic points of the system throughout western New York State.

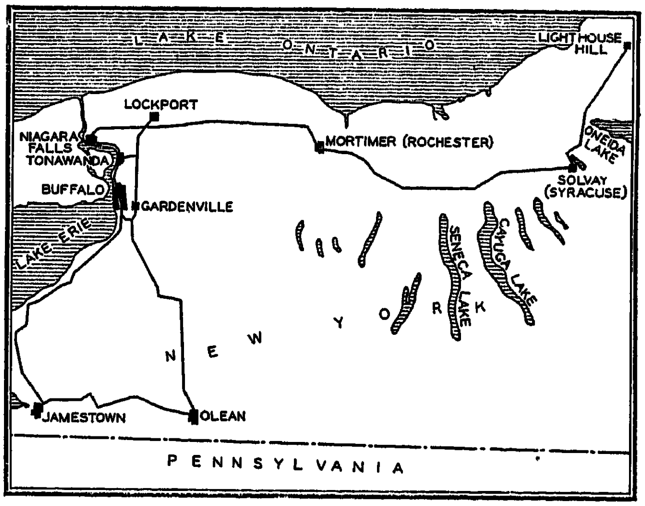

FIG. 1

Part I will be discussed later in this paper, as it is concerned mostly with inter-office and Buffalo city communication.

Parts II and III were considered and fully discussed by the various operating men concerned. Following this discussion and the adoption of various modifications proposed by the operating staff, the telephone company was authorized to provide the facilities outlined in the plans.

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[1] Elec. Engr., Buffalo, Niagara & Eastern Power Corp., Buffalo, N. Y.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

REMOTE METERING

The load supervisor's office had been moved to the Electric Building in Buffalo. This made it necessary to centralize operating telephone lines at that point and provide remote metering installations from the generating plants at Niagara Falls and Buffalo. Lines were leased from the telephone company for this purpose, and by means of the meters the load supervisor gets an accurate picture of the load on either station at any time of day.

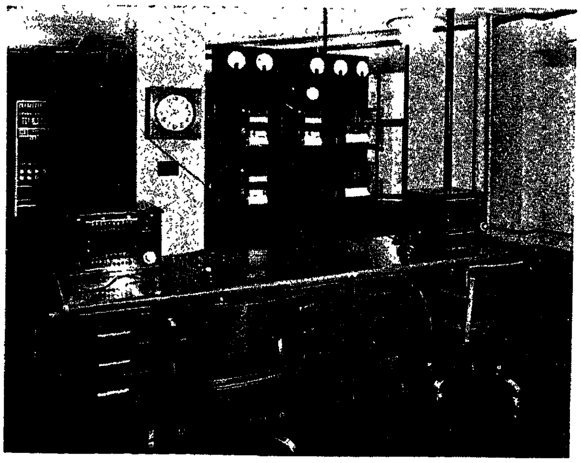

FIG. 2—REMOTE METERING INSTALLATION IN LOAD SUPERVISOR'S OFFICE AND TWO 20-LINE, SINGLE-SIDED SPECIAL DISPATCHER'S TURRETS IN OFFICE OF SYSTEM OPERATOR

Three recording and three graphic meters are provided. One of these shows the total load in kilowatts on Huntley Station number one, which is a 25-cycle steam-electric station, and the second shows the total load on Huntley Station number two, which is the 60-cycle steam station. The third is connected to Harper Station, the switching unit at Niagara Falls, and shows the load on units 19 and 20 in Schoellkopf hydroelectric station. These are the regulating generators at the station, and the meter reading, in connection with data supplied to the supervisor, makes the total load on the station available at a glance.

Huntley Station is about five miles from the supervisor's office and Schoellkopf Station is about 20 miles away. The meters are operated by three separate circuits leased from the telephone company. These are shown in Fig. 2.

FULL TALK CIRCUITS

Three vital points of the system are tied together from a communication standpoint by lines leased from the telephone company on a 24-hour a day basis. While these lines are built and maintained by the telephone company as part of its regular toll facilities, the power company has as full use of them as it would have of privately owned lines.... and without the responsibility of maintenance. In the event of trouble on these lines, the telephone company is usually in a position to make available other lines for reaching the same points.

The points thus tied to the division load supervisor's office are the Buffalo steam plant, the system operator's office at the Niagara Falls hydro plant and the Lockport switching station. Through Lockport, the load supervisor can also talk to Mortimer, Lyons, Solvay, and Syracuse. Using the automatic equipment in the Buffalo office, he can also reach Gardenville (just outside the city), Jamestown, and Olean.

Lines were also leased from the telephone company to connect the four main switching points of the western division directly with each other. Niagara Falls, Lockport, Gardenville, and the Buffalo steam station are so tied in that any one can call directly and talk to the other three.

These four points have district load supervisors, and by means of the leased circuit a two to four party conversation may be held directly by the men. The load supervisor for the western division gives his orders to the district supervisors over circuits reserved for that purpose entirely, and the line connecting the four points directly is reserved for the use of the four district supervisors in direct intercommunication.

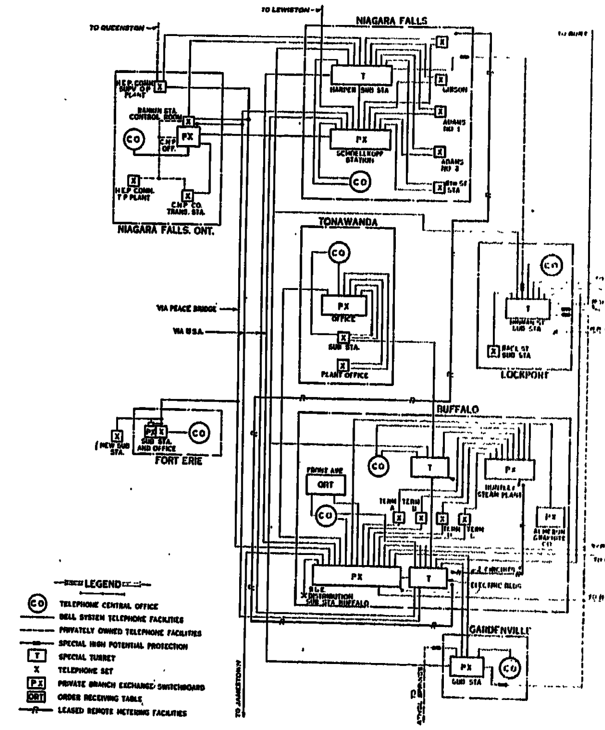

FIG. 3A—COMMUNICATION FACILITIES, BUFFALO, TONAWANDA, AND NIAGARA FALLS

Buffalo, Niagara and Eastern Power Company

The arrangement of communication circuits at Buffalo is shown in Fig. 3A.

Lines entering the division load supervisor's office in Buffalo, as well as those entering each switching station are brought to a special dispatchers' turret. One telephone instrument connects the operators to the entire communication network, the turret being so simplified that the operator needs only to throw a key to call the station he wants.

Turrets are of three capacities, 10 line, 20 line, and 40 lines, and are provided in both single and double face to meet various requirements. The turret in the division supervisor's office at Buffalo is a 20-line single-face installation.

Through these turrets, communication lines of various types can be tied together. Dial central office lines, dial extension lines, common battery extension lines, magneto-battery central office lines, magneto-battery leased lines and magneto-battery privately owned lines can be interconnected in the turrets. For example, the load supervisor in Buffalo may call Syracuse on a leased line, be switched through the turret and talk to Lighthouse Hill using the privately owned line from Syracuse to that point. This eliminates the delay and error danger involved in relaying the message. The turrets provide that only one call like this may be switched through at a time, however. This limitation was purposely provided in order to avoid making the load supervisor a telephone operator.

Another advantage of the turret is its speed. All lines end in keys rather than plugs, and it is faster and easier to switch the key than to pick up a plug and make the connection.

While the communication system was being planned, several instances were discovered where operating needs could not justify the leasing of lines on a 24-hour a day basis. Such lines were desirable from an operating standpoint, but the operating department alone did not feel justified in incurring the necessary expense.

It was found, however, that if these circuits could be reserved for the operating department at certain hours and open to other departments the rest of the time, the expenditure was well worth while. These circuits were accordingly leased, with a resulting saving in long distance toll calls and closer contact between district offices and the main office.

INTERCONNECTION OF PRIVATE LINES

By what has gone before, it might be assumed that private lines owned by the various companies before the consolidation, were entirely discarded, but this was not the case. Where private lines were available and in good condition, protective equipment was leased from the telephone company, in accordance with the power company's agreement, in order that private lines might be connected to leased lines to provide intercommunication when desirable.

Power company privately owned lines usually follow the transmission line right-of-way, and where these lines interconnect with telephone company circuits there is danger of damage to equipment and possible personal injuries due to the building up of voltage on telephone lines through induction or direct contact between communication and power transmission wires. This hazard has been eliminated through the installation of protective equipment leased from the telephone company.

Where the interconnection of communication lines is in a station building, horn gap arresters located in a sheltered spot on the outside of the building are installed on the lines. These are set at 0.05 inches, to operate at about 5,000 volts. The lines then pass through disconnecting switches, at which point fuses are provided and thence to a second arrester. This second arrester is set for as low a voltage as is consistent with that normally induced on the private line. The ground of the arresters is connected to the station ground bus. The lines then pass through a transformer for further protection, since it acts as an insulating barrier. From the secondary side of this transformer the lines pass through a standard telephone protector to the point of connection with the telephone company's conductors.

Where privately owned lines connect with telephone circuits at points distant from buildings, a similar installation is made on poles. One pole is set between the last high-tension line pole and the first telephone company pole for the installation of protective equipment.

In order to take care of excessive ground potentials where telephone equipment is installed in power and larger switching stations, two methods are used; insulating transformer, and distant ground.

The distant ground method is suitable in the case of smaller stations and where the telephone instruments can be placed so that persons using them are insulated from the ground potential of the station. Telephone equipment and wiring are adequately insulated from all grounds and grounded structures that are subject to excessive potential variations, and the equipment is connected to a ground a sufficient distance away to be free from the influence of power station ground potential variations.

With the insulating transformer method it is not necessary that the telephone instruments be placed in insulated locations in the power station. Where grounding is required, the telephone equipment is grounded to the power station ground, and the outgoing lines pass through an insulating transformer before they connect with telephone company circuits.

All equipment on the power station side of the transformer is grounded to the station ground; all equipment on the telephone company side of the transformer, within range of the influence of power station ground potential variations, is carefully insulated from that influence. The insulating transformer is the barrier between the power station ground potential variations and the telephone company's system.

CARRIER CURRENT

Carrier current is used in addition to the leased lines and privately owned lines. Briefly, in the event that not everyone is familiar with this means of communication, it is a system which puts carrier current for voice transmission at very high frequency on the power lines, the frequency of this carrier current being in the radio frequency range.

Sets are installed at Niagara Falls, Buffalo, Gardenville, Olean, Jamestown, Mortimer, Solvay, and Lighthouse Hill. These sets are single frequency duplex, providing two-way communication between stations and in general are rated at 50 watts.

Each telephone instrument on this system is provided with a dial for selective ringing. Various stations are assigned dial numbers, as on the conventional dial telephone system, and any one station may call any other by dialing it directly. Where leased lines are available, the carrier-current system is not used to any great extent under normal conditions because of the better quality of voice transmission on the leased lines. However, each set is tested thoroughly every day to make sure that it is in operating condition in the event of an emergency.

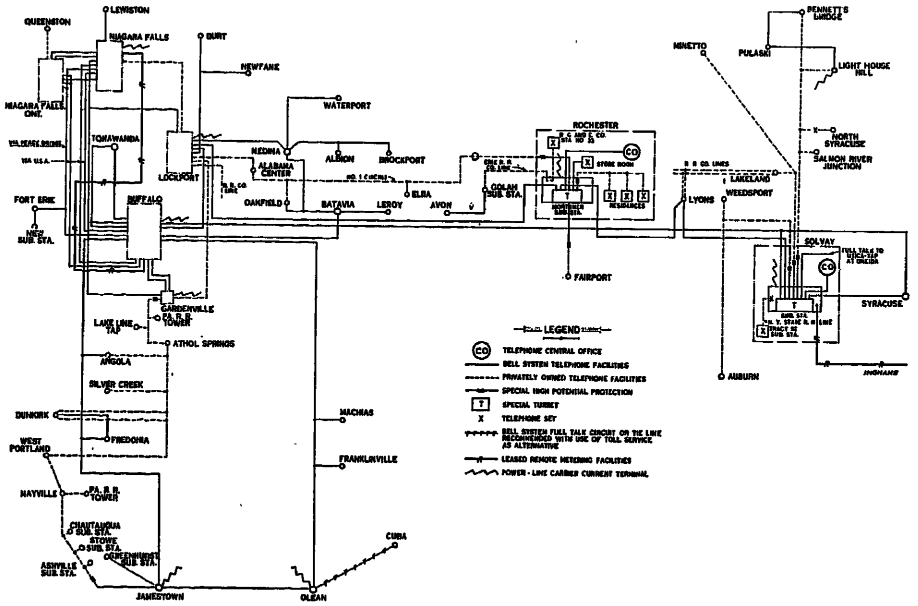

FIG. 3B—SYSTEM COMMUNICATION PLAN

Buffalo, Niagara and Eastern Power Company

In situations where leased lines are not available, such as between Solvay and Lighthouse Hill, the carrier-current equipment is much more valuable. There is also an arrangement whereby the carrier-current equipment at Lighthouse Hill, which is on the edge of the Adirondacks, can be used for communicating with the generating stations in the St. Lawrence district. Its operation under these conditions is entirely satisfactory. Fig. 3B shows the power system communication plan.

Practically all the lines leased from the telephone company are in cables, reducing to a minimum the probability of failure during storms. In addition, where two circuits are leased between the same points, the circuits follow entirely different routes. This also helps to minimize the possibility of storm damage.

In this connection there is an important consideration in regard to power company private lines. Usually these lines are on transmission line rights-of-way in order to avoid the expense of securing separate rights-of-way. Communication is most needed during periods of destructive storm, and private communication lines often go out when transmission lines fail. The leased circuits usually follow different routes from the transmission lines, providing an additional factor of safety.

Prior to the establishment of the present communication network, a particularly disastrous sleet storm, swept across practically the entire territory. Many of the stations were cut off at the beginning of the storm and the private lines were severely crippled. Of course the first job was to restore the power lines.

Two interesting occurrences during this period are worthy of mention. Extensive use was made of telephone company toll circuits and one call from Albany to Buffalo was routed entirely around the storm area via Montreal and Chicago. Short-wave radio was also used. Amateur stations in Buffalo and Syracuse, as well as at a number of intermediate points, broadcast messages which were relayed by local telephone to our switching stations. At times during the storm period the carrier-current system was the only means of communication between load centers.

Communicaton for the operating department was carefully planned following an exhaustive study of the needs and daily traffic. As it is now laid out, the load supervisor has at least two different channels of communication with every major switching and generating station on the system, as shown by the Buffalo district diagram in Fig. 4. The communication system now installed has met every practical test so far satisfactorily.

INTERDEPARTMENT COMMUNICATION

With the establishment of western division headquarters in the Electric Building, population of the building doubled in less than a year. Prior to 1930, three separate switchboards were maintained for the three separate companies, with resulting confusion.

Employees of one company calling the employees of another first signaled their own operator and asked for the other company. When the second operator answered, they asked for their party. With the rearrangement of departments by floors, irrespective of companies, employees working side by side were often on two different switchboards. There was also a great deal of congestion on the tie lines between company switchboards, and a large staff of operators was required to handle the traffic. Customers were also confused and there was a considerable number of calls intended for one company received on the switchboard of one of the others.

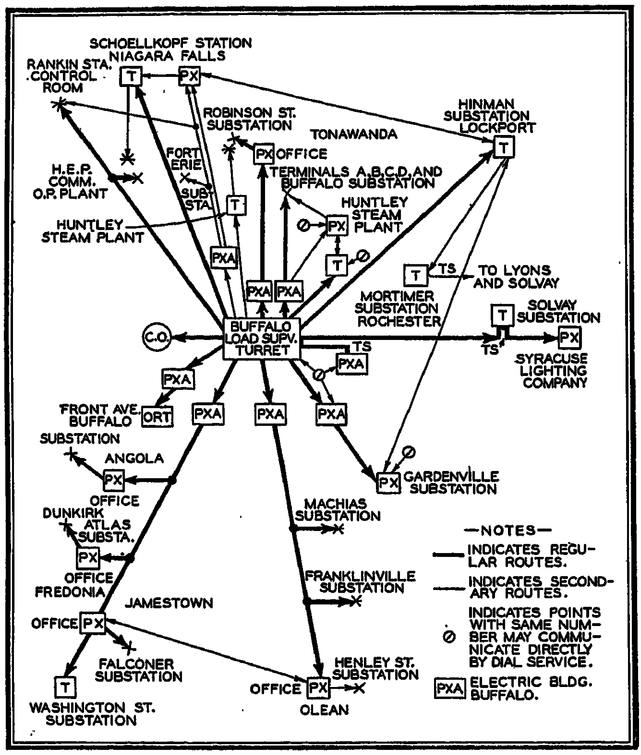

Fig. 4—Buffalo Load Dispatcher's Circuit Diagram

This situation was somewhat relieved by bringing all the boards together, but the traffic problem, particularly on interdepartment calls, was still present.

The problem was solved by establishing a dial private branch exchange leased from the telephone company, for interdepartment communication. Calls between departments are now dialed directly and are not handled by operators. Calls to the telephone company's central office are also dialed through directly and do not pass through the manual switchboard. Operators are now concerned only with incoming calls to the general offices; customer and all service calls being handled by a special method which is explained later.

The company's general switchboard, following the adoption of the dial system, was cut from five positions to three positions, only two of which are used in normal operation. The staff of operators was reduced from nine to five, despite the fact that the number of telephones served by the private branch exchange has increased from 189 to 325, with a corresponding increase in telephone traffic.

The extra position on the manual switchboard is not needed in normal operation. But in peak traffic, such as that occasioned by service interruptions, it is possible to put an extra operator at this position to help in handling customer calls. While trouble calls usually go to an entirely separate order table receiving apparatus, as described later, customers have a habit of calling the general office when the customers' service department is busy. This occasionally occurs during an unusual service interruption. This extra position helps to relieve the peak caused when customers in trouble call the general offices instead of the customers' service telephone department.

In some of the smaller offices of the western division, dial equipment has been installed to give better service to customers. In time of trouble, single position boards in these offices have been swamped by customers calling in, and the operating staff, trying to call out in order to clear the trouble, has been handicapped.

With dial equipment, the operating men can dial out on a separate group of outgoing trunks and the operator can devote her entire time to answering incoming trouble calls until the trouble has been cleared. The results have been quicker restoration of service and better treatment of customers.

Where the dial system is in use, one telephone instrument is provided for both inside and outside calls. On an inside call the number of the extension desired is dialed directly. On an outside call, 7 is dialed and when the second dial tone is heard, indicating that the instrument is connected with the telephone company's exchange, the number wanted is dialed.

Since the installation of the dial system, time consumed in completing both inside and outside calls has been cut in half. Employees have become thoroughly familiar with the dial telephone and find it faster, more accurate, and generally more satisfactory. The new system has also ended the irritating habit of having a telephone operator put in a call and keep the person called waiting on the line until the caller is ready to talk. It has been found that people have acquired the more courteous habit of being ready to talk when the person they call answers.

INCOMING CALLS FROM CUSTOMERS

Public relations dynamite lurks in every telephone call. Executives who ponder upon the public relations problem would do well to listen in on some of the incoming calls from customers and learn at first hand how employees deal with customers over the telephone.

Under the method previously used by the company, customer calls came to the general switchboard. The customer made his request to the telephone operator who knew by experience what department was wanted. Usually the operators were all busy with other calls, and this delayed answering incoming calls. Customers were not always sure what department they wanted. It was a common occurrence for a customer to ask for the purchasing department, and upon being connected, say that he wanted to purchase an appliance.

Calls to have service cut in or cut out and similar requests were routed to a commercial table. Here, after the customer had repeated his request, the message was taken and relayed to the department handling the work.

Customers who reported trouble were connected with an order table in the distribution department, operated by men, and while they handled their work well, the telephone contact with customers was not always as pleasing as it might have been.

Entirely aside from the cumbersomeness of this arrangement, there were several undesirable features from the standpoint of public relations:

1. The customer was forced to make his request two or three times to different people, explaining his trouble to each one.
2. The company caused the customer loss of time and patience.
3. Often customers hung up before the proper department was located, with a resulting loss of both good will and business to the company.
4. No record was made of how any given case was handled and whether or not the customer was satisfied; no one, with the possible exception of one department head (whose department had happened to handle the particular case) knew what service had been given.
5. There was no follow up to make sure that the customer was satisfied.

Following the survey and report by the telephone company, a department was established known as the customers' service telephone department. This is a centralized point where all customer telephone calls regarding connections and disconnections of electric service, interrupted service, bill complaints, and requests for information are received.

Calls are received over a special group of 18 central office trunk lines which terminate in what is known as an order receiving table. This is a telephone switchboard in the form of a long table, with places for seven persons on each side facing each other. Green lights in the center of the table indicate a call instead of the ordinary telephone bell. The board is so multipled that the same call may be taken at any one of three positions, and a white light flashes when the call is answered.

Each service representative is equipped with headset receivers and a chest transmitter, leaving both hands free. From all positions at the order table, direct lines run to the meter and trouble departments and the order table files, making it possible to get information quickly from these departments while holding the customer on the line. In addition, 10 tie lines connect the order table with the dial switching equipment of the private branch exchange, making it possible for the service representatives to pass the call along to any of the 325 extensions from the company's regular switchboard in the event that the customer wants to talk further to some particular person. In this event, the service representative gets the company employee while holding the customer call, explains what is wanted and thus obviates the necessity of the customer's repeating his request. Through these tie lines, service representatives may also get information from any one of the 325 extensions on the company's regular exchange.

Incoming trunks to the order table pass through the regular exchange, but give no signal to the operators there. However, if the call has been made in error and the customer really wants the regular general office switchboard, the service representative gets the switchboard operator over one of the tie lines and asks her to connect the person on the trunk number to Mr. Blank. Although the customer has made a mistake, he is transferred without a word to the right extension. When customers call the general office switchboard in error, they may also be transferred without trouble to the customers' service telephone department.

The customers' service telephone department answers all customer calls to Cleveland 5260 directly. This number is so listed in the telephone directory that customers should not get the wrong number, but if they do their call is passed along to the right switchboard without any inconvenience to the calling party. The young ladies who comprise this department were carefully selected and put through a course of training extending over a six weeks period before the department was put into operation. During this time, they were in all the various service departments, getting a background regarding the work done so that they might handle customers' requests intelligently.

The staff of the department includes fourteen attendants and a supervisor. The department is in operation 24 hours a day, every day in the year. The usual load on the department is about 1,200 calls a day, but during times of general trouble over a section of this city, calls rise to a peak of 3,000 or more. When the lines are normal, attendants who are not needed "double" as typists and filing clerks, but are ready to take up their duties as attendants the moment a peak impends.

When desired information can be obtained in a few moments, the attendant "holds" the customer on the line and provides it; when considerable time is needed, the customer's number is taken and the information is telephoned back when it is secured.

By having the customer calls come into this centralized point instead of directly to the private branch exchange switchboard, the necessity of the customer being cross-examined by the private branch exchange operator to find out what the customer's desire might be is obviated. After this, the call was referred to the department that might be involved, where again the customer was requestioned and if he had not been connected to the right department, transferred to another telephone and again questioned, much to the irritation of the customer. The customer's telephone service bureau not only receives the call, but completes the entire customer contact without transferring the call to another person or to another department. This arrangement not only provides for speedier handling of customer calls, which is essential to giving real customer service, but allows all calls of this nature to be handled by a group of people who can specialize in this type of work. The equipment is shown in Fig. 5.

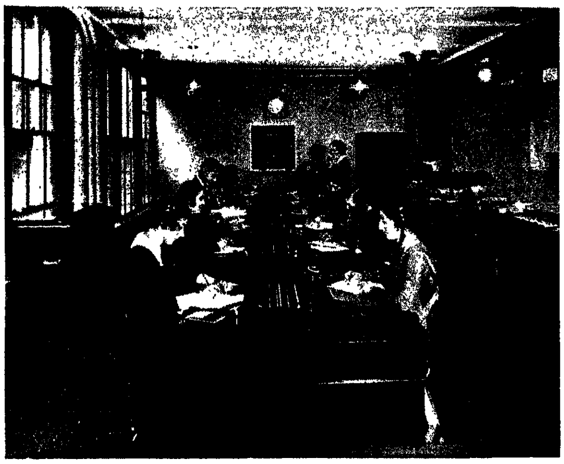

Fig. 5—Order Table—Buffalo

Teletype Machines

Calls to have service cut in or out, bill or service complaints, and trouble calls are handled by the department directly. The customer provides the information and the operator follows it through to completion. For this purpose, five teletype machines are provided, affording direct communication with the meter and distribution departments in the Service Building, two miles away. The teletype installation is shown in Fig. 6.

A telephone typewriter instrument is an electrically operated machine which has a keyboard and other mechanical parts similar to a regular typewriter machine but with this difference; that the sending machine can be at one location and a similar receiving machine can be at a distant location either in the same building, the same city or two widely separated cities. The machines are so arranged that whatever is typed on the sending machine, such as an order, a letter or other information, is instantaneously transmitted by electrical impulses over wires to the receiving machine. These impulses operate the keyboard of the receiving machine in such a manner that it types the message at the receiving point exactly as it was typed at the sending point. Through the medium of five of these machines in the customers' telephone service department, all orders and reports of trouble are immediately sent to the Service Building for prompt attention.

All service requests are kept in duplicate in a pending file. This file is inspected every morning to make sure that all promises of the day before have been kept. In this way, the customers' service telephone department provides a constant check on the service rendered by other departments.

There has also been installed a monitor observing set which taps every company telephone line. By means of this, samples are taken of telephone conversations carried on by employees and these are used as a basis for training employees in the correct use of the telephone. This work has been so arranged that there has been no charge of "spying." Each department knows in advance when it is to be observed over the monitor. Samples are taken verbatim by a stenographer at various periods of the day for several days. These are discussed later at a meeting of employees of the department observed and means of improving the different conversations are pointed out.

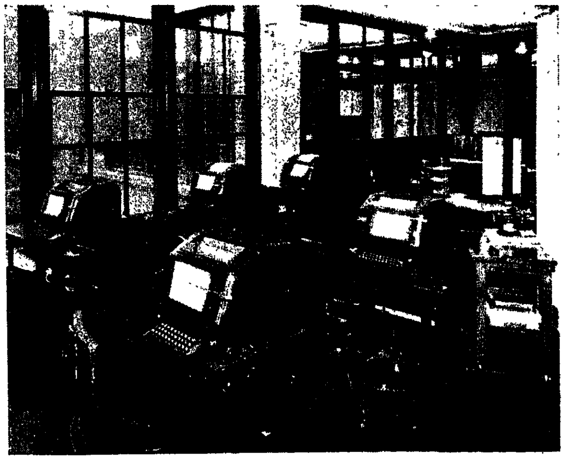

Fig. 6—Five No. 15 Sending and Receiving Telephone-Typewriter Instruments

Three equipped with special platens for positive drive and remote control, two equipped with standard platens—one with remote control

The vital importance of telephone contacts with customers has been realized and for that reason steps have been taken to see that their impressions of the company gained over the telephone, are favorable.

It is believed that the system of communication which has been set up in the western division of the Niagara Hudson system is practical, efficient, dependable, and up-to-date. The telephone company deserves a great deal of credit for the way in which it handled the complete survey of our system and for the coöperation it has given us in working out our communication problem.

Communication on the Arkansas-Louisiana-Mississippi Interconnected System

BY E. C. STEWART[1]
Non-member

Synopsis.—This paper describes the communication facilities in use on the Arkansas, Louisiana and Mississippi Power & Light Companies' interconnected system, and describes the operating performance of the communication equipment.

Carrier-current telephone equipment is used to a large extent for relatively long distance communication, the longest distance being 459 miles. The reliability of this means of communication under unusual storm conditions is discussed. The experience resulting from over six years use of carrier-current telephony for load dispatching purposes is described.

INTRODUCTION

THE Arkansas, Louisiana and Mississippi Power and Light Companies are operating in these three states an interconnected transmission system comprised of a total of approximately 1,800 miles of 110-kv. lines. Supervision of the operation of this system is centered in the dispatcher's office at Woodward Switching Station near Pine Bluff, Arkansas. Operation on the southern part of the system is handled from the dispatcher's office located at Jackson, Mississippi. Other systems which operate in parallel with this are the New Orleans Public Service, Memphis Power and Light, Southwestern Gas and Electric, and the Arkansas-Missouri Power Companies. Each of these has its own dispatching force which handles inter-company operating matters with the Pine Bluff dispatcher.

It is the purpose of this paper to describe the method of communication used in the operation of this system, which is largely by means of carrier-current telephony.

HISTORY

Prior to 1925, while this system was yet small, all communication was carried on by means of the toll service of the telephone company and considerable use is still made of this service, some for dispatching, but the larger part for business matters.

Upon the completion of Remmel Dam near Malvern, Arkansas in the latter part of 1924 and connection of this into the system over a 66-kv. line to Pine Bluff and a 33-kv. line to Little Rock, need of fast and reliable communication was anticipated. In considering means of obtaining such service, it was natural to favor the shortest route possible. Such a route was covered, except for a matter of about eight miles, by a privately owned and operated telephone system. This, however, was only a single-circuit line and in rather a poor state of repair. It would thus have been necessary for the power company to string a circuit of its own after satisfactory arrangements had been made, and to replace a large number of poles in order to obtain a strong and reliable line. The cost of this was such that it was felt to be too high when the reliability of such a line was compared to the heavier construction employed on the power line.

It was thus that carrier current came up for consideration, and the result was the purchase of two Westinghouse carrier-current sets. Operation of this equipment was begun the first of 1925, and the original set is still in operation at Remmel Dam, although the set at Pine Bluff was replaced by another early in 1926, because of the creation of the Woodward Switching Station about two miles west of the original location of the Pine Bluff carrier-current equipment.

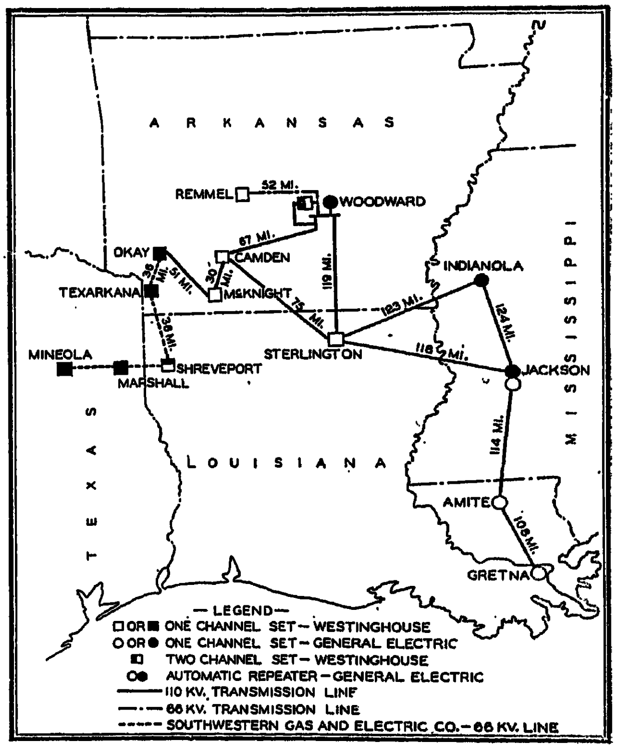

FIG. 1—LOCATION OF CARRIER-CURRENT SETS

Results of this first installation were so satisfactory that the use of carrier current was decided upon for the Sterlington Station and connecting lines when completed early in 1926, and accordingly five more carrier-current sets were purchased. This gave carrier-current connection from Pine Bluff to Remmel Dam.

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[1] Arkansas Power & Light Co., Pine Bluff, Ark.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

El Dorado and Crossett in Arkansas; Sterlington in Louisiana, and Vicksburg and Jackson in Mississippi. It is not deemed necessary here to go into the details of how some of these sets have been moved from place to place as system changes caused certain substations to lose importance, which made it more desirable to have the carrier-current facilities at other points.

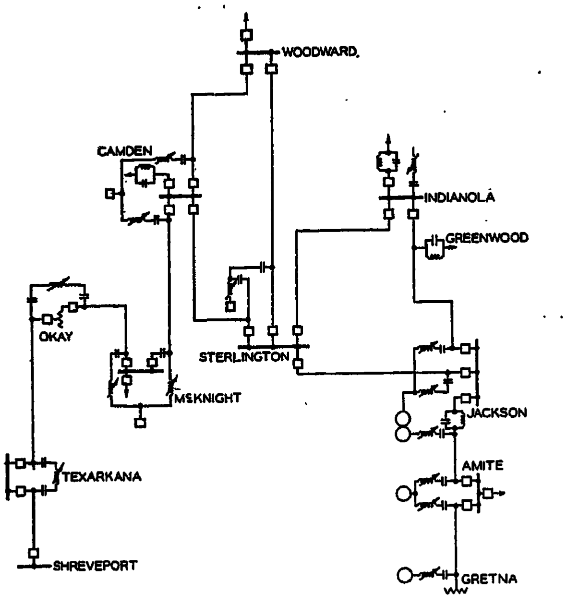

Fig. 2—Location of By-Pass Equipment and Traps to Confine Carrier Frequencies to Definite Channels

Early in 1930, operation was begun on the carrier-current channel between the Pine Bluff dispatcher and the Southwestern Gas and Electric Company dispatcher at Shreveport, Louisiana.

Later in 1930 the extension of the system to New Orleans was made and it was necessary to provide some form of communication in that direction. Communication was desired from both the Pine Bluff and Jackson dispatchers to New Orleans and the Amite, Louisiana substation, a main switching point about half way between Jackson and New Orleans. It will be noted from Fig. 1 (which shows only the portion of the system covered by carrier-current channels) that considerable distances are involved in such a connection, the shortest route over the transmission lines from Pine Bluff to Jackson being 237 miles and from Jackson to Gretna substation (which is just across the river from New Orleans) 222 miles, or a total distance from Pine Bluff to New Orleans of 459 miles. Such distances are most economically covered according to our experience by carrier-current equipment, supplemented in the few cases necessary by the use of the toll service of the telephone company. Without going into detail, the purchase of new equipment was decided upon, and a total of five type KCA-1 sets and one type KCA-100 set was made. The KCA-1 equipments were installed as follows: one at Pine Bluff, Arkansas, one at Indianola, Mississippi, two at Jackson, Mississippi (arranged as an automatic repeater) and one at Gretna, (New Orleans) Louisiana. The KCA-100 equipment was installed at Amite, Louisiana.

The installation of all of the above sets created a new channel and permitted the move of the Westinghouse equipments from Indianola and Jackson to other points on the system. One is to be installed at Carpenter Dam, now nearing completion, which is located at the headwaters of the lake created by Remmel Dam, and the other will be installed at some other point, the proposed location at present not being fixed.

Preparation of Channels

Fig. 2 indicates what has been done in the preparation of the carrier channels over this system by means of by-passing equipment and frequency blocking on unused portions of the system where necessary. It will be noted that dependence is placed between Pine Bluff and Sterlington, and from Sterlington to Indianola or Jackson upon at least one side of the transmission line loops being intact, and it has been our experience that it is in extremely rare cases that the communication channel is broken between Pine Bluff and the aforementioned points.

The location of carrier-current equipment on the lines of the Southwestern Gas and Electric Company, namely, at Okay, Texarkana, Shreveport, Marshall and Mineola have been indicated because of the relation they bear to the operation of the carrier equipment on the Arkansas-Louisiana-Mississippi system. These sets operate on a separate frequency channel and it has not been found necessary to date for either party to resort to frequency blocking between the two systems. No

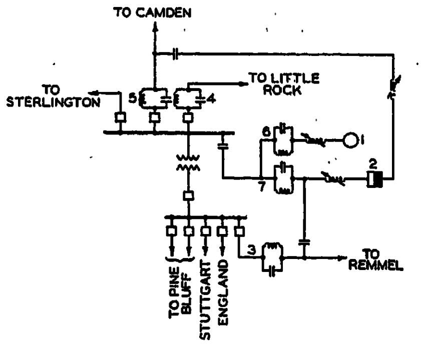

Fig. 3—Schematic Diagram of Method of Coupling, Tuning and Frequency Blocking in Use at Central Dispatching Point at Woodward Switching Station of the Arkansas Power & Light Company Near Pine Bluff, Arkansas

Legend: 1. General Electric carrier set.
2. Westinghouse carrier set, operating on two channels.
3. Resonant chokes for termination of Remmel channel.
4. Resonant chokes to prevent loss of energy from General Electric set.
5. Resonant chokes for termination of Camden circuit at frequencies used in communication with Shreveport.
6. Trap circuit to exclude Westinghouse carrier from General Electric set.
7. Trap circuit to exclude General Electric carrier from Westinghouse set.

attempt will be made here to describe this company's installation other than the portion involved in communication between the Pine Bluff and Shreveport dispatchers. This is accomplished on a separate frequency channel by the use of a second receiver at Shreveport and at Pine Bluff, both transmitters being arranged to deliver the proper frequency when calls are made between these points. The frequencies in use are 65 and 84 kilocycles. The by-passing circuits shown in Fig. 2 at Camden, McKnight, Okay, and Texarkana are for preserving this communication channel.

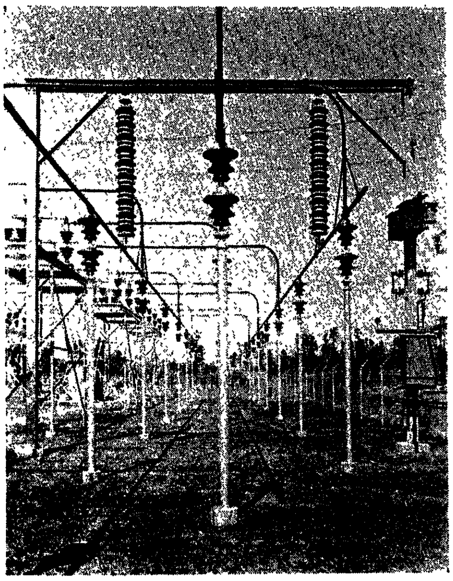

FIG. 4—WOODWARD 110-KV. BUS COUPLING

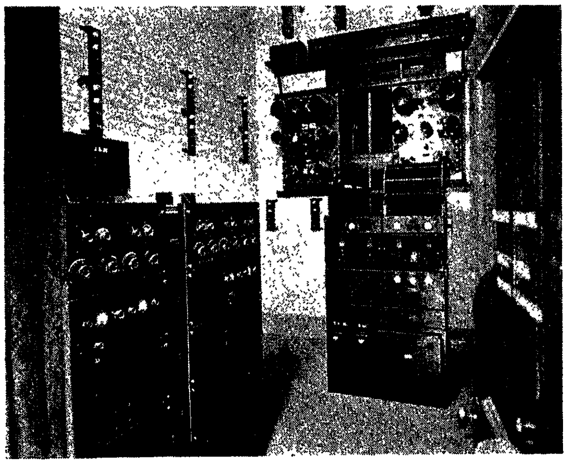

FIG. 5—WESTINGHOUSE CARRIER-CURRENT EQUIPMENT AT WOODWARD

COUPLING

With the exception of the Remmel Dam set, which uses antennas, all coupling is by means of capacitors. There are only two kinds in use on the interconnected system: the Westinghouse suspension units and the General Electric cable type. No failures have occurred on either of these during the past two years, which covers the period of our experience with capacitors.

Fig. 3 shows a somewhat unusual application adopted at Woodward Switching Station. Here, we have coupled to the 110-kv. bus over one set of capacitors both the Westinghouse and General Electric carrier-current equipments for the channels used in communication on the interconnected system. The General Electric equipment is operated at 70 kilocycles and the Westinghouse at 40 and 55 kilocycles. Operation of this arrangement has proven satisfactory.

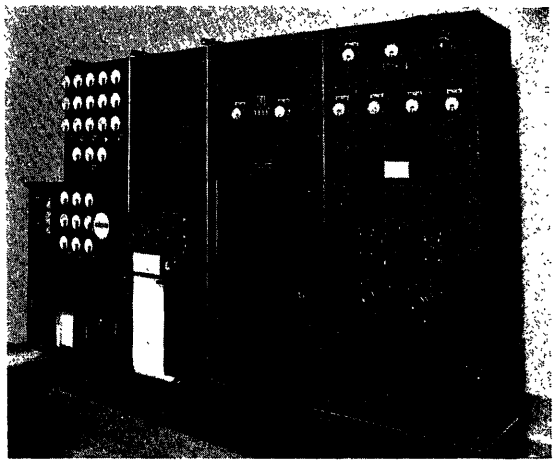

FIG. 6—GENERAL ELECTRIC CARRIER-CURRENT EQUIPMENT AT WOODWARD

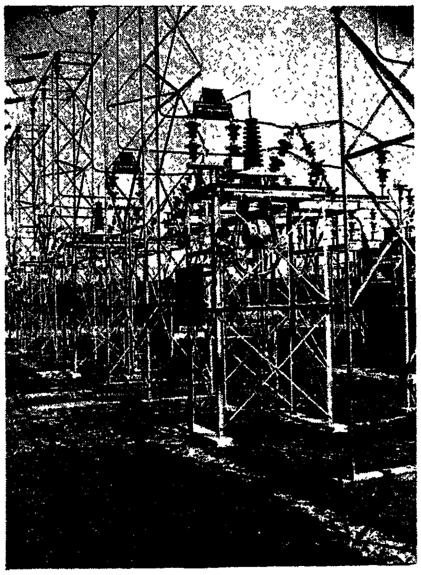

FIG. 7—CABLE-TYPE COUPLING CAPACITORS AND CARRIER-CURRENT TRAPS AT JACKSON

PROTECTION

There have been two occasions at Remmel Dam, when the 66-kv. wires came in contact with the antenna wires, for observing how well the protective system functioned. Neither case resulted in damage to anything except the protective equipment itself. On one of these occasions the Remmel operator was talking on the carrier current at the time of the trouble and experienced no physical inconvenience whatsoever.

OPERATION

The carrier-current installation on the interconnected system, supplemented by the use of toll service and one or two leased or specially arranged circuits, is primarily for use by the dispatcher, but considerable business traffic is handled by the dispatching force outside of any rush period by means of messages, which are relayed by the dispatcher to a station operator, and thence to the party addressed.

A check of the number of times the Westinghouse transmitter has been on at Pine Bluff for the past year shows that the total of placed and received calls averages over 3,400 per month. A similar check on the General Electric set at Pine Bluff over the last five months shows that it has averaged close to 1,400 operations per month. A record was kept over three months of the total time of use and indicates that one and one-quarter minutes per conversation is representative of the average communication.

In the operation of the carrier-current equipment on the interconnected system, communication between outlying stations has not been allowed since it has been of little advantage in the system operation for any of these outlying stations to communicate with any other point than the Pine Bluff dispatcher. Pine Bluff has therefore been made a "central" and is called by the mere taking down of the telephone. It is necessary though, for Pine Bluff to dial the various stations to call them, but to save time and provide a rapid check on the selective ringing system, the successful call of a station is evidenced by the automatic starting up of the distant transmitter which has been called.

To date, carrier current has not been provided along the lines for the use of patrol or maintenance men. Reports of routine patrolling are not turned in by telephone unless some condition found warrants immediate attention, in which case the nearest available form of communication is used. Emergency patrolling to locate line breaks has been made during the last three or four years by means of aeroplane, weather permitting. Report of observations is made in a good many cases by messages dropped in pasteboard containers to some substation operator who relays the information to the dispatcher. Exact structure numbers are given, to fix the location, through the use of line maps specially prepared for this purpose and distinguishing markers on top of key structures, which are readily visible from the plane.

RELIABILITY

There is a number of instances on record which convince us that carrier current affords very reliable communication. A few cases are mentioned briefly below.

In April 1927, during flood, carrier current was the sole means of communication at Remmel Dam for a couple of days.

The latter part of April and the first part of May 1927, during the great flood, carrier current was the only form of communication for several days to the Sterlington Station.

Several times, during storms, when other means of communication were not available uninterrupted service was maintained over the carrier current.

Communication Facilities of a Metropolitan Power System

BY P. B. JUHNKE[1]

Member, A. I. E. E.

Synopsis.—A description of the communication needs of a power company serving a large metropolitan area, including detailed information with respect to load dispatching problems and use of remote metering facilities as an effective aid in conducting load dispatching operations.

ELECTRIC light and power, in all its metropolitan perfection, is not entirely independent of several other agencies of public service. Not the least of these is communication, which makes the light and power system the living organism which it really is.

Because the electric power system is everywhere, so far flung in supply centers and activities of various kinds, it depends more upon communication in the discharge of its obligations than most other forms of business. For this reason an examination of the communication facilities of the Commonwealth Edison Company is of interest.

Fig. 1 shows a map of Chicago, with all fixed plant locations of the Commonwealth Edison Company. This fixed plant includes not only generating stations and substations, but also service buildings and yards, garages, etc. These many locations are served by about 19 telephone switchboards, with a total of about 2,600 telephone stations. The main board with seven sub-boards in the Edison Building is indicated by the double star. The sub-boards outside of the Edison Building are indicated by a single star.

LOAD DISPATCHING

Of special interest is the employment of communication in the technical direction and supervision over the operation of the system. The technical group especially entrusted with this function is the load dispatcher's office, located in the main office building at 72 West Adams Street, and in direct private wire communication with all generating and distribution stations and most substations.

The load dispatcher's office, shown in Fig. 2, is composed of three sections, two dealing with the routine of load dispatching and one with the performance of the system. They are designated as:

1. Load dispatcher, section No. 1
2. Load dispatcher, section No. 2
3. Load control section

The first two are charged with the responsibilities which have always characterized this work. Responsibility for supply of power to all principal distribution centers, direction of switching in connection with work to be done, responsibility for safe working conditions on service elements removed for work, responsibility for correct procedure for putting into or removing from service any system elements. Each one of these two sections has directing charge over approximately three generating stations and a total of approximately 175 substations and transformer vaults. It has direct communication with all generating stations and most substations. With important load centers it has a number of direct telephone wires from its own telephone switchboard.

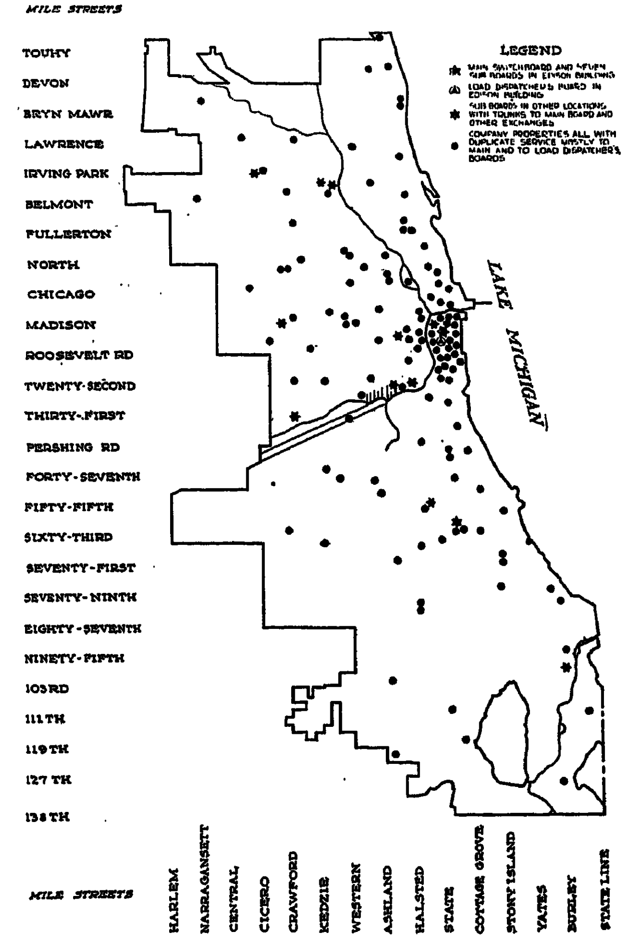

FIG. 1

The load control section is of relatively recent

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[1] Chief Load Dispatcher, Commonwealth Edison Co., Chicago, Ill.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

origin, and is charged with supervision over the supply of power from the different generating centers selected to contribute to same. It further has supervision over the connecting tie line elements between the stations, mostly of 66,000- and 132,000-volt order. This supervision not only embraces the generating stations and interconnections within the city limits, but also the interconnections with and the supply from the generating stations located outside of the city and having responsibility of contributing to the Commonwealth Edison Company requirements. This section has direct telephone communication from its own two-position board with all generating stations and 66,000-volt switching centers, all of which, in reality, are part of the system interconnections.

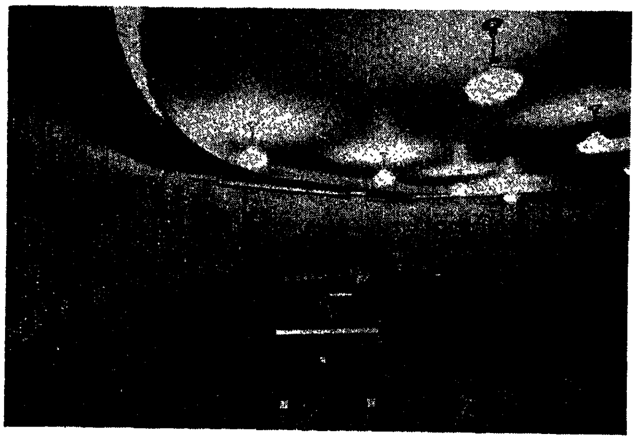

Fig. 2—Load Dispatcher's Office

Before this section was organized its functions were exercised by the load dispatcher, making this work one of his regular functions. It is in this phase of load dispatching that considerable changes have been experienced lately, and in which the communication plant has taken an increasingly more important part.

The load dispatcher's duties have always included control over the distribution of the load between the various generating stations. This was comparatively simple in the days when an electric system consisted of one principal generating station and perhaps a few reserve stations. When four or five generating stations appeared on the scene, all with varying performance ability, the task took on a vastly different aspect. The load has to be divided between all of them in a manner taking account of their relative performance efficiency.

The correct principle of operation was recognized from the beginning, *viz.*, to put the largest amount of load on the most efficient stations, and lesser quantities on those of successively poorer efficiency. Progressive development was, therefore, possible only in regard to methods employed in conforming to the aforesaid principle. A series of definite steps in the development of the methods now in force are distinctly discernible.

Earliest methods, when a new station came on the scene, provided for that station, usually the more efficient one, to carry all the load possible, predicated upon its capacity, the outgoing lines and the size of its interconnecting ties. This method was intelligent, but sometimes made the required performance of the older station rather difficult. When a third station of still greater efficiency appeared, the situation became more involved and compelled the load dispatcher to pay more attention to the instantaneous total load and to apportion it between the three as the economies of the situation dictated. This was done from hour to hour and worked well, but was very laborious because it required almost continuous readings to distribute the load properly.

From this developed the load totalizer, which collected the loads of individual stations in the load dispatcher's office. In the collection of these data, telephone lines were employed for transmission of the power readings. This was a considerable step forward, but still required continuous direction on the part of the load dispatcher, based on the totalization. It was followed by another development, known as the load totalizing scheme with reverse indication. In this scheme the totalization effected in the load dispatcher's office is sent back to each of the principal generating stations, and on this totalization, with indication to each station, is based the scheme of operation. Each generating station is given a load chart showing every station's individual responsibility toward the system for all the different load values encountered in the course of a day or longer, as is shown in Fig. 3. In the preparation of this chart full and complete account is taken of the relative efficiency of different stations, and the distribution of load between the different stations is planned with a view to leaving the bulk of the load on the base load stations, and progressively less load quantities on the less efficient ones.

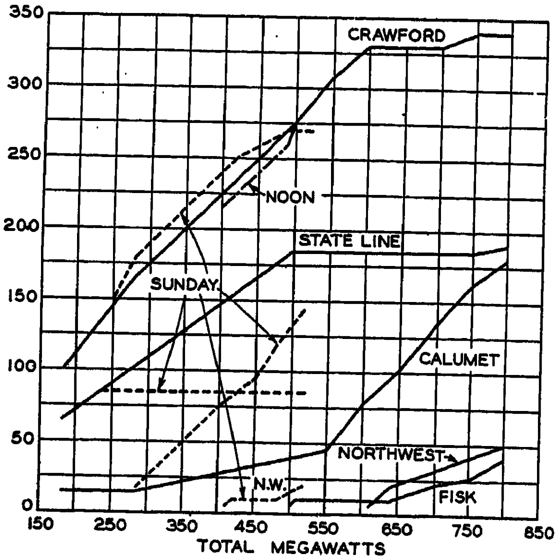

Fig. 3—Commonwealth Edison Co. 60-Cycle Load Schedule

It is recognized that even inefficient stations, that run mostly for peak purposes, must be given a certain load considerably ahead of the time they are desired to carry the peak. It is also recognized that sometimes less efficient stations must be kept running in certain locations in the interest of adequate system or district protection. All these requirements can well be indicated on the load schedule and this fact makes the scheme practically automatic, as each operator at every moment can see his own share of the total load and conform thereto. The load control function simply has to concern itself with seeing that the schedules are adhered to and that the proper departures are made when and if changing system conditions so dictate.

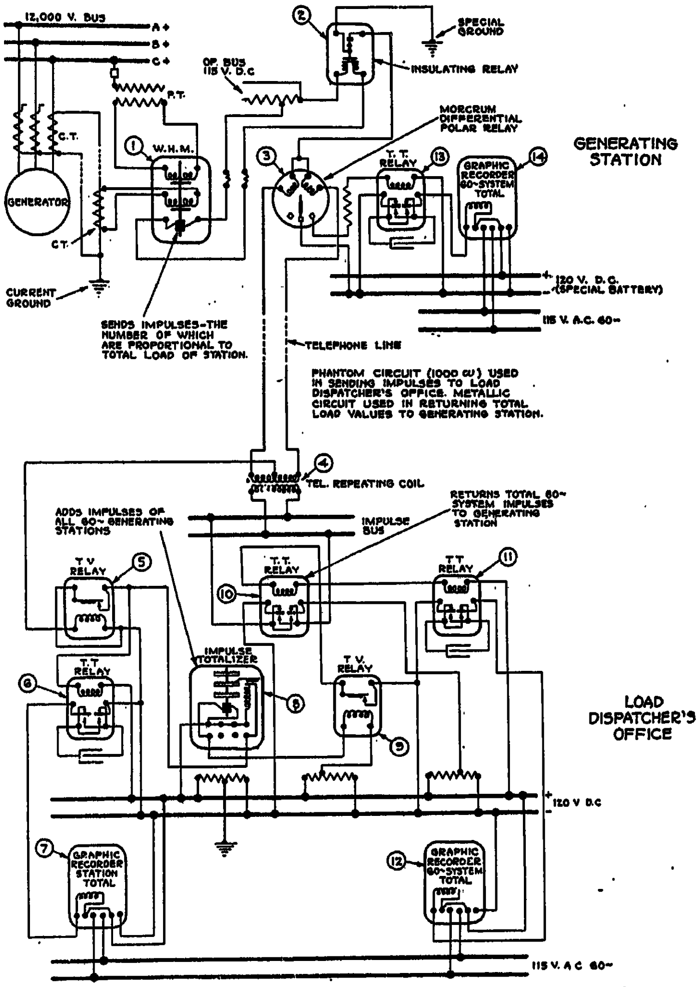
12,000 V. BUS
A+
B+
C+
OP. BUS 115 V. D.C
P.T.
C.T.
GENERATOR
C.T.
CURRENT GROUND
①
W.H.M.
SENDS IMPULSES-THE NUMBER OF WHICH ARE PROPORTIONAL TO TOTAL LOAD OF STATION.
②
SPECIAL GROUND
INSULATING RELAY
MORCRUM DIFFERENTIAL POLAR RELAY
③
T. T. RELAY
⑬
GRAPHIC RECORDER 60~SYSTEM TOTAL
⑭
GENERATING STATION
120 V. D.C. (SPECIAL BATTERY)
115 V. A.C. 60~
TELEPHONE LINE
PHANTOM CIRCUIT (1000 ω) USED IN SENDING IMPULSES TO LOAD DISPATCHER'S OFFICE. METALLIC CIRCUIT USED IN RETURNING TOTAL LOAD VALUES TO GENERATING STATION.
④
TEL. REPEATING COIL
ADDS IMPULSES OF ALL 60~ GENERATING STATIONS
IMPULSE BUS
RETURNS TOTAL 60~ SYSTEM IMPULSES TO GENERATING STATION
T V RELAY
⑤
T.T. RELAY
⑩
T T RELAY
⑪
T.T RELAY
⑥
IMPULSE TOTALIZER
⑧
T V. RELAY
⑨
LOAD DISPATCHER'S OFFICE
120 V D.C
⑦
GRAPHIC RECORDER STATION TOTAL
⑫
GRAPHIC RECORDER 60~SYSTEM TOTAL
115 V. A C 60~

FIG. 4—SCHEMATIC DIAGRAM OF REMOTE METERING SYSTEM

REMOTE METERING SYSTEM

The information required for proper load control is obtained largely from the remote metering systems, details of which appeared in an earlier article by the author.* Briefly the arrangement consists of utilizing received alternating current impulses for operating the controlling coils of an indicating graphic recorder.

IMPROVEMENTS IN THE REMOTE METERING SYSTEM

Instead of balancing the effect of the impulses by mechanical means, some of the recorders have recently been changed to operate on a wheatstone bridge arrangement. The coils of the meter act as the galvanometer, in which there is no current as long as the impulses are constant. As the impulses vary the circuit becomes unbalanced and current flows through the meter coils, tending to close a contact, causing the operating motor to run in a direction to indicate more or less load, depending on the direction of current through the meter coils or galvanometer. The operating motor also moves a sliding contact on a resistance coil, tending to restore the balance of the wheatstone bridge circuit.

With this new meter circuit arrangement it is not necessary to have all the meter elements installed on the load dispatcher's board. This has made it possible to install several of these recorders in a relatively small space, all of which can be read by the men at the load control switchboard. The charts are all controlled by the same synchronous motor, and therefore all record for the correct time, so that there is no question about comparing the chart for any specific time.

In this metering scheme as installed in the Commonwealth Edison Company metallic telephone circuits are used exclusively, but the fact that the impulses can now be transmitted by the carrier-current system has materially enhanced the usefulness of the system, especially for metering distant stations.

On account of the high maintenance costs of the mechanical totalizers, research work is being conducted in an effort to replace these totalizers and relays with vacuum tubes.

This installation no doubt makes possible the most intelligent operation of large interconnected systems. The task of directing is continuous and practically automatic, and the economies gained in plant operation of a system of moderate geographic extent more than warrant the cost of the equipment and the incidental telephone line rental.

Discussion

F. R. Innes: The function of communication is the transmission of information so that operation may be controlled. Information may be expressed in speech, intelligible to the human mind or it may be expressed in some other manner to which mechanical and electrical devices are receptive. To the latter class belongs remote metering.

In systems where generation stations are separated and must, for over-all economy, be operated with the most favorable division of load between them, the remote metering installation is a valuable tool. It is quite possible and it does happen on systems where load control is not closely watched that load swings at one station or another due entirely to transient conditions, may be very large, much larger than is good for the operation of the system.

A remote metering system, quickly responsive to changing load conditions, bringing to one point and to one man a complete picture of the system load, makes possible the reduction of differences from the ideal conditions of load division between stations and results in a much more stable system operation. It is possible, with such close control, to keep the regulating station secure in its function and to prevent the usurpation of its job by another station that may for any reason be more responsive to changes in system load.

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*"Budget-Plan Load Dispatching." by P. B. Juhnke and L. N. Moore, *Electrical World*, Vol. 89, pp. 1317-1320.

Cooperative Study of Power System Communication

Results in Improved Facilities

BY C. A. BOOKER[1]
Non-member
and
M. E. CLARK[2]
Associate-member

NEW England Power Association operates a large group of interconnected wholesale and retail electric companies in a highly developed industrial area. Energy is generated at eleven major hydro stations on the Connecticut and Deerfield Rivers, and transmitted on four 66-kv., four 110-kv., and two 220-kv. circuits to the load centers in central and eastern Massachusetts and Rhode Island, where interconnection is made with several large steam generating plants by other high-voltage lines.

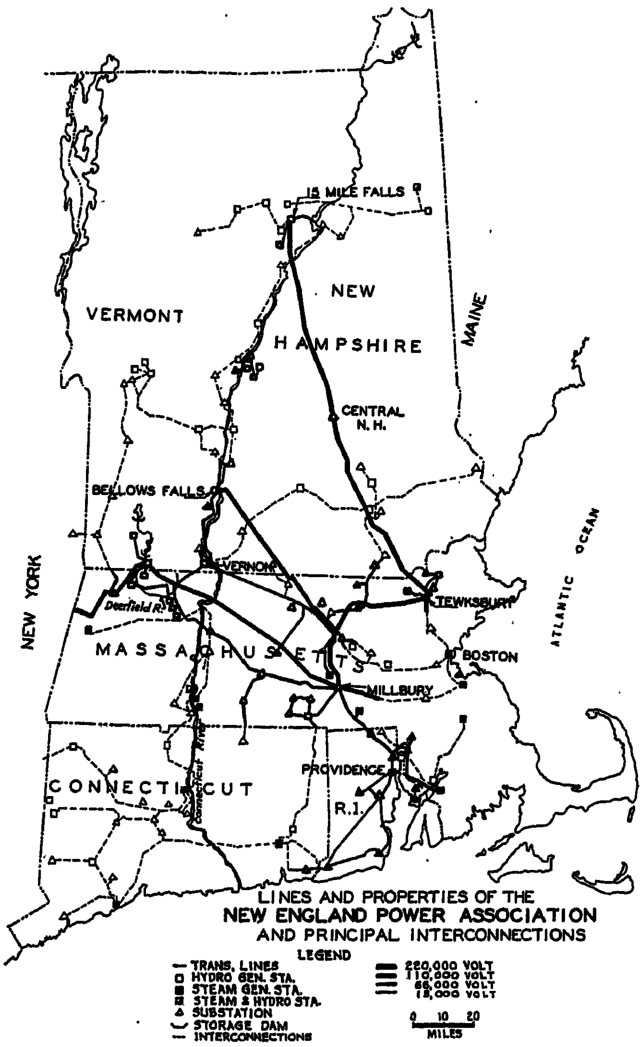

FIG. 1

To assure maximum economy in operation, a centralized control over all producing and distributing units is necessary. This control is exercised by the operating engineer through the Dispatching Department, which has its headquarters at Millbury. The extent of the power system and location of the various transmission lines is shown in Fig. 1.

In order to obtain the advantages of unified management the territory served is divided into districts each having a district manager to whom report the managers of the individual retail companies, a superintendent in charge of maintenance and operation of generating stations, substations and transmission lines, and a distribution engineer in charge of distribution layout for the retail companies in his district. In addition each district has a resident representative of the Treasury Department.

TYPES OF COMMUNICATION REQUIRED

Thus for the operation and management of these companies, three distinct types of communication are required. The first is concerned with the operating control of the power system; the second has to do with customers' service and ordinary commercial requirements of the individual companies; and the third is concerned with the administration, or executive and engineering control of the territorial districts. The specific requirements of each type of communication service will be discussed in detail.

OPERATING CONTROL

The most important factor in the operation of a system comprised of a large number of generating and distributing units is the System Load Dispatching Department. It is the duty of this department to coordinate the operation of the various parts so as to achieve maximum economy. This objective can be gained only by very prompt and reliable communication from department headquarters at Millbury to each individual unit.

An analysis of the actual functioning of the department discloses a considerable number of closely related methods through which the coordination and control is exercised.

1. Complete centralized control over production and load distribution.
2. Control over every piece of apparatus available for service.
3. Supervision of system tagging and safety work,

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[1] New England Power Association, Boston, Mass.

[2] New England Tel. & Tel. Co., Boston, Mass.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

both during ordinary maintenance and emergency repair work.

4. Forecast and scheduling of coming operation about 15 to 24 hours in advance.

5. Arrangements for interchange of power with other interconnected systems.

In order to plan intelligently the operation of the system, the dispatcher must have available complete data on existing conditions. These data are secured by hourly reports from the various stations which transmit by telephone the necessary information, of which the following items are examples: production, sales, voltage, water elevation, machines in operation and others available for service, condenser operation, precipitation reading, gate and flashboard operations, etc. In fact, everything having a bearing on system operation is included in the hourly reports.

Reports are also received in regard to apparatus or line failures and arrangements made with the proper departments for the necessary repairs. During such repairs, elaborate safety precautions are taken to prevent energization of equipment on which work is being done.

To facilitate the transmitting of reports as to the location of failures as well as to expedite maintenance and return of equipment to service, telephone stations are desirable at fairly close intervals along important transmission lines. It has been found to be good practise to have such stations located at about six-mile intervals.

Recently it has been found advantageous to delegate dispatching authority over certain limited areas to district dispatching offices. These district offices exercise the first three functions of dispatching under the general supervision of the chief system dispatcher at Millbury, who in turn is responsible to the superintendent of power control in the operating engineer's office. This results in a unified organization in which methods are standardized and by which policies and procedures may be speedily dispatched without misunderstanding. It is evident that this method of operation requires instant, dependable, and continuous communication between all points involved.

CUSTOMERS' SERVICE

The individual retail companies usually require a private branch exchange system to provide a flexible communication service for receiving customers' and other outside calls, as well as to handle interdepartmental calls. These switchboards must be supplied with ample facilities including outside lines and private branch extensions to handle all calls without delay. In the larger communities 24-hour service is essential, which necessitates constant attendance of one or more telephone operators or the use of a full dial P. B. X.

The telephone extensions to the Customer's Service Department are so arranged that all calls involving service of anything from flat irons to radios or electric refrigerators are received at one place. This is in order to enable such calls to receive prompt and sympathetic treatment without irritating transfers from one department to another.

ADMINISTRATION

As a network of communication lines converging at Millbury is necessary for the operating control of the power system, just so a similar network converging at Boston is convenient for the administration of the commercial and engineering aspects of the business.

The provision of a relatively few lines provides such a network between the executive offices and the territorial offices by which the business is greatly expedited. Also, by interconnection made at the territorial office switchboards, economical and speedy communication is available with every part of the system. Thus when designing the telephone system for administrative purposes, flexibility is kept uppermost in mind, it being particularly necessary to consider carefully the effect on the whole network when any addition or change is being planned.

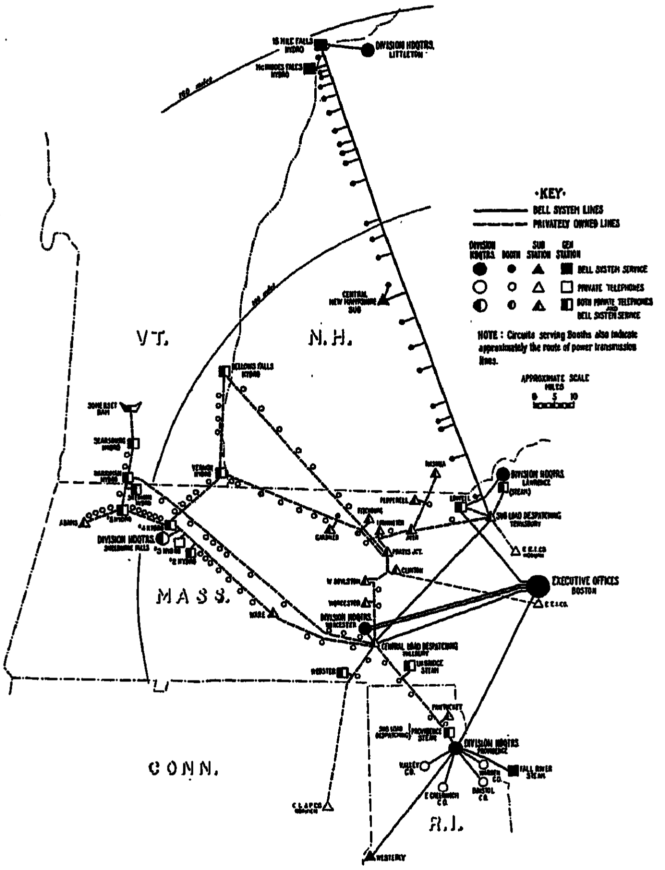

FIG. 2—PRINCIPAL COMMUNICATION CIRCUITS OF NEW ENGLAND POWER ASSOCIATION

EXISTING COMMUNICATION ARRANGEMENTS

The extent and character of existing arrangements for supplying the above requirements are shown in Fig. 2.

On a map of this reduced size it is of course not possible to indicate the location of all P. B. X.'s of which there are twenty altogether.

HISTORY OF PRIVATE TELEPHONE SYSTEM

Before entering upon a discussion of the methods by which the above requirements have been fulfilled and coordinated, a brief historical review of the beginning and development of the private telephone system will provide some necessary background.

At the time of the construction of the first transmission line in 1908 from Vernon to Clinton, it was believed by the designers that instant communication was necessary between the two termini, as well as with intervening stations in order to insure proper operating control. This resulted in stringing a telephone circuit on the same towers with the power line conductors. As additional generating capacity and transmission facilities were developed, the private telephone lines were extended along with the power lines either on the power structures or on separate wood poles at the edge of the right-of-way. Thus the telephone facilities constructed by the power company grew from a line 50 miles in length to a system having 600 miles of circuit.

Probably the principal reason for the construction of this private system was that at that time commercial telephone service was supplied, in this territory, by a number of independent and uncoordinated companies. These companies were not then equipped to supply promptly and efficiently the communication needed to operate the power system.

Regular subscriber service was of course used in the same way in which it is a necessary adjunct to every business, although it was a common practise to use the private dispatch lines wherever possible to save toll charges. However, traffic on the private lines eventually became so congested that it was thought advisable to prohibit their use for any purpose except actual operation of the power system, and in some cases it became necessary to provide relief in the form of additional service. Careful consideration indicated that service suitable for this need could be secured most economically by the use of regular commercial telephone service.

When the executive and engineering offices were concentrated at Boston and affiliations with distributing companies increased, the great increase in messages radiating from the Boston office justified the use of a leased network for handling the administrative business.

By 1928 the number of messages handled by the private telephone system at the central dispatching office at Millbury had grown to over 600 per day in times of normal operation or about twice that number during periods of trouble. It thus became necessary to make further improvements in the communication arrangements, which now handle about three times the above number of calls daily.

More knowledge of the fundamental requirements for each type of service was needed as well as a definite picture of the desirable arrangement and concentration of such services. It was also recognized that both privately owned lines and regular commercial telephone service were involved, and that an intelligent study of the situation required a thorough knowledge of modern developments in the communication field, as well as intimate familiarity with the operation of the power system.

At a meeting of Power company executives with those of the New England Telephone and Telegraph Company, this need was expressed with the result that a cooperative study was entered upon to determine how to obtain improved communication service from existing facilities, as well as to plan for coordinated extensions.

JOINT STUDY

This study considered all parts of the system and its objectives were as follows:

1. The determination of existing communication facilities, methods of operation and service usage.
2. The determination of present and future communication requirements.
3. The analysis of these requirements to determine what improvements or changes should be made, and what additions were required.

A large part of the initial survey has been completed, and it has become apparent that the changing nature and growth of requirements merit continued and sustained study on a joint basis. The survey has already resulted in improvements of which the following are typical.

Modification or rearrangement of private branch exchange systems serving local areas, districts, or divisions has provided a more adequate and efficient handling of the needs of the business. In some instances, it has been possible to effect substantial economies in the cost of service coincident with the rearrangement. Somewhat allied with this problem has also been the conversion from regular toll service to leased line service in all cases where this is justified. Leased service is adopted when the cost of toll calls between two areas increases to the extent that the leased service becomes particularly attractive, due consideration being given to such factors, as accessibility and usage, as well as cost.

LOAD DISPATCHING TURRETS

Probably the most interesting of the special station and switchboard equipment developed are the load dispatching turrets shown in Figs. 3 and 4. The desirability of these turrets was indicated in the joint study, and they were designed and furnished by the Telephone company as a part of its service. These turrets are conveniently placed at the dispatcher's desk and serve to terminate and interconnect communication circuits associated with the private branch exchange system. They have been so designed as to meet the following outstanding requirements of the load dispatchers.

It was desired to provide access to all lines and yet minimize the actual work of telephone operating which is required of the dispatcher. This was accomplished by locating the turrets conveniently, by using switch keys instead of cords and plugs, and by providing means for the station P. B. X. operator to handle all calls not intended for the dispatcher. At the same time the load dispatchers must have full control of all the lines at times of system disturbance or at night when the regular switchboard was unattended. This requirement was met by arranging for permanent patching of all lines from the P. B. X. to the turrets whenever desired.

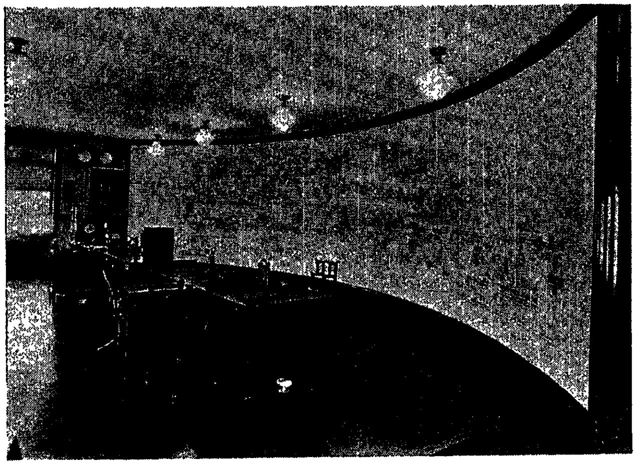

Fig. 3

Visual as well as audible indication of incoming calls and their status is important because of its many advantages. For example, the visual indications of incoming calls appear on the turret as fast as the calls come in, and remain until answered. Thus the amount of traffic waiting to be handled is at all times apparent, and the number of dispatchers on duty can be adjusted depending upon its volume. In this connection a visual indication of a busy line is also provided at all positions so that, when a call is answered by any dispatcher, the others are notified to that effect and take care of the next unanswered call.

These various conveniences are accomplished while all but two telephone instruments are eliminated from the dispatcher's desk, one for the private line and one for the Bell system lines.

Transmission, Protection, and Signaling

A vital part of every study in the review of existing facilities and in the planning of new ones has been that of transmission, that is, the grade of "talk" obtained. It is not unusual to connect two or more lines for communication within the private network. In such cases a line which is designed to give satisfactory transmission between its terminating P. B. X's may be entirely inadequate when connected to another line to reach a more distant P. B. X. or station. It is, therefore, important to determine beforehand what interconnections are desirable in order to meet such situations in the design of the circuits.

Of equal importance is the matter of protection from abnormal electrical voltages which may be impressed upon the communication circuits by lightning, induction from power lines, or ground potential conditions. Existing installations have been inspected to make sure that protective equipment was properly installed and suited to the specific conditions. On new or proposed installations the proper protection arrangement is determined in advance by observations, tests, and calculations.

On long circuits or on circuits involving several bridges, it is important also to consider the signaling arrangements best fitted to meet the particular requirements. These have been found to vary somewhat depending on the needs of the specific case.

Noise Treatment—Private Lines

The joint survey of the communication facilities owned by the power company is of interest. It was recognized that consistent treatment and maintenance would be required to keep the lines in proper condition from the standpoint of noise and transmission, and that some of the lines were much noisier than was believed to be necessary.

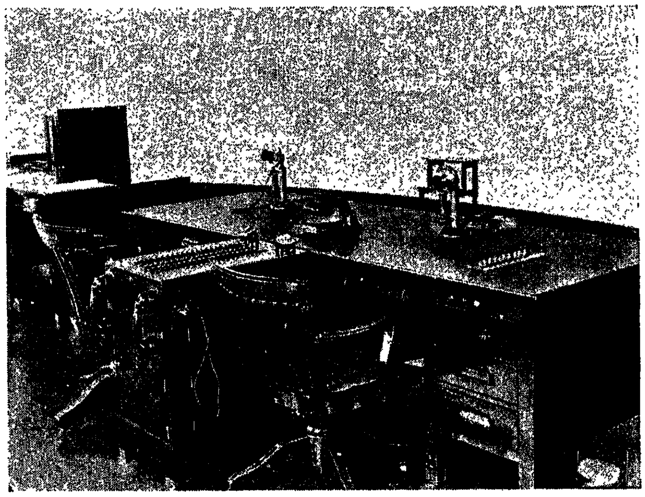

Fig. 4

A systematic attack on this problem was made, beginning with a complete field inspection and survey. As a result of this survey, all necessary tree trimming, replacement of broken insulators, etc., were accomplished as well as the preparation of a complete exposure and transposition diagram of all the lines in the system. At the same time measurements were made of the noise, both metallic and to ground, which was present on all of the lines and on the various parts of these lines. From the exposure diagrams obvious transposition unbalances were noted and corrected. The noise survey provided the basic data from which an intelligent attack could be made on testing and locating the sources which caused the noise.

The next step was to design a combination of equipment which would accurately measure insulation resistance, series unbalances, etc., so that bad joints, leaky insulators, and other contributing causes could be located without sacrificing adequate protection to the testers from the induced voltages present on the telephone lines. The work of cleaning up the lines with the use of this testing equipment is finished. Although all the data are not yet assembled, it can be stated that this testing and clean up work has resulted in marked improvement of the noise conditions on the lines and it is planned to continue the use of this testing equipment as a regular part of the maintenance work.

FIFTEEN MILE FALLS PATROL SERVICE

When, in 1929, it was decided to proceed with the construction of the Fifteen Mile Falls power development with its 220-kv. transmission system, authorization was secured on the basis of constructing the usual wood-pole telephone line parallel to the power lines. The effect of induction on the communication system was carefully considered by the power company and discussed with the telephone engineers on the joint study basis.

This discussion resulted in the telephone company's suggesting as an alternative proposition that this service be leased from it. A preliminary plan of the details of obtaining leased service at the various patrol stations was made. A thorough consideration and discussion showed that the desired service could advantageously be obtained in this way. This resulted in a decision to enter into the proposed arrangement on a trial basis.

The prime influence in arriving at this decision was the ability of the telephone company to furnish one or more duplicate paths of communication in case of trouble with the regular path. Such duplication is available on the existing private system by virtue of its layout in loop feeds but was unobtainable on the Fifteen Mile Falls line except at very considerable expense. Another factor considered is that within a few years the telephone company plans to have sleet proof construction throughout the length of the line. A third factor was the lower annual cost.

The layout of this communication circuit is indicated in the upper right hand portion of Fig. 2. It is designed to serve precisely the same function for load dispatching and for patrol service along the transmission line as do the privately owned lines paralleling the other transmission lines.

The features of design and the maintenance arrangements which insure the desired continuity of communication service may be of interest. The leased circuit is routed over regular toll lines from Tewksbury to Fifteen Mile Falls with a permanently bridged tap to the central New Hampshire substation. Access to the 23 patrol booths on the transmission line is given by lateral spur lines extending from central offices through which the main line passes. The average distance from the main line to the patrol booths is five miles and the average spacing between successive booths is five miles. This line is under the complete control of the power company and the services of regular telephone operators are not required, except when exchange service is desired from a patrolman's booth.

An interesting equipment feature is the arrangement whereby the patrol station spurs are normally disconnected from the main circuit, but which permits them to be connected to the main circuit at will by the operation of a switch at the patrol booth. With this arrangement, shown in Fig. 5, the closing of the switch at any patrol station causes a relay at the central office to connect the patrol loop to the main circuit. The switch is normally left open so that the bridging losses of the patrol station spurs may be avoided.

Where Line is Bridged at a Magneto Office

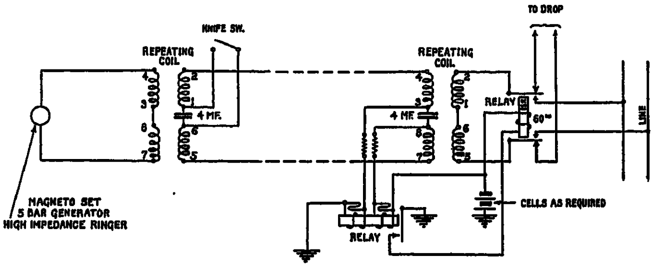

FIG. 5—PATROLMAN'S LINE CIRCUIT

Special for New England Power Company Tewksbury-Barnet Line

Provision is also made to enable the patrol station to signal the operator in case exchange or toll service is desired. This desirable feature is accomplished by connecting the back contacts of the bridging relay to a drop in the central office. It provides greater continuity of service, for, should the relay fail to operate, a patrol station will automatically signal an operator when the patrolman rings on the line. Connection can then be made either to the leased lines or to the toll or exchange network of the telephone company.

Adequate transmission is obtained on this circuit by the use of vacuum tube repeaters at three intermediate central offices. These repeaters also make it possible to carry on satisfactory conversations between Millbury and Littleton when the respective tie lines are connected.

Field tests indicated the necessity for special high-voltage protective equipment at the Tewksbury substation and the Fifteen Mile Falls generating station, and also at the central New Hampshire substation to prevent interruptions of telephone service due to rise of station ground potential at times of power line fault. These tests indicated that the ground potential in case of power line fault will rise above the corresponding central office ground enough to operate standard substation and central office protection and put the telephones out of service. The power line is *Y* grounded at Tewksbury and Fifteen Mile Falls and the station ground at these points is therefore susceptible to such voltages in case of any fault throughout the entire length of the 220-kv. line.

The protection provided consists essentially in isolating the telephone plant in the vicinity of the power station from the rest of the telephone plant by using insulating transformers in all telephone lines on the load feeding the power station. Transformers insulated for 25,000 volts between the windings are used. They are protected from lightning by 3,000-volt lightning arresters where the line adjacent to them is open wire. These transformers are mounted on *H* structures in the aerial telephone plant feeding the stations.

Recognizing the important part played by communication in the operation of the power system the maintenance practises which have been placed in effect are designed to ensure the highest degree of dependability and continuity of this service.

Among the points covered in the maintenance routine, the following have been emphasized as of primary importance:

1. One man has been designated, to whom trouble on any part of this circuit is reported, either by the power or telephone company employees. This man coordinates and administers all maintenance or repair work on this circuit.
2. At times of trouble in the outside plant, he arranges to have it cleared in the shortest possible time.
3. A cabinet of patching jacks has been installed in every central office which was not already equipped with a toll testboard or toll patching jacks. Both the spur lines and the main line are terminated in these jacks. Regular toll circuits have been designated for use at times of circuit failure on the leased line and also appear in these patching boards so as to facilitate the setting up of emergency service.
4. Instructions are set up with test men and with various central offices to patch with these circuits at time of trouble and to re-route the entire base circuit if necessary to maintain continuity of service.
5. Arrangement is made for routine tests and for manual connection of spur lines at offices not equipped for test to the main circuit so that tests can be made from distant test boards.

CONCLUSIONS

Although the communication requirements of the New England Power Association have presented some unusual problems, joint consideration of these requirements has resulted in a satisfactory communication system. The provision of adequate communication is essential to the operation of the power company, and in order that this may be accomplished economically and with minimum duplication of effort, as the requirements change in the future, it is planned to continue the joint survey work.

Reestablishing Excitation of a Loaded Alternator in Parallel with Others

BY D. D. HIGGINS[1] and E. WILD[2]
Member, A. I. E. E. Associate, A. I. E. E.

Synopsis.—The paper describes operating tests with large turbo generators under load and gives a résumé of answers to a questionnaire, bearing on the phenomena accompanying the interruption of the direct-current excitation supply, followed by reclosing after a short interval.

The object of the investigation was to determine, if possible, a reasonably safe operating procedure that could be followed in reestablishing normal conditions on a large turbo generator whose excitation had been interrupted while carrying load.

The authors conclude that the reexcitation of a generator without withdrawing it from the bus is a justifiable and safe operating procedure and the one that will restore all conditions to normal in the shortest time.

These conclusions have been verified by twelve prearranged tests, five "experiences" in the local company and seventeen "experiences" by other companies. In all of these cases the field switches have been reclosed without trouble of any kind.

* * * * *

ONE of the early questions which arose in the parallel operation of alternating-current generators was, "what will happen if the field circuit is opened while a generator is carrying load and in parallel with other generators?" This proposition is somewhat academic and no doubt has been solved to the complete satisfaction of students and others using laboratory set-ups or small generators whose behavior, in so far as customers' service was concerned, was of no serious consequence.

Operators of large power stations and interconnected systems have disposed of the question in various ways as evidenced by replies to a questionnaire. It was found that there was a lack of conclusive data bearing on the behavior of turbo alternators when operated with an open field and, in general, it was the impression that something very serious might result if the field was reestablished before disconnecting the generator from the bus. The usual practise was therefore to take the unit off the system, reexcite it and resynchronize.

While the foregoing was the general feeling, there was no evidence to support it; in fact, the evidence produced was negative. As the size of individual units increased and large, single machines constituted a considerable percentage of a station's capacity, and an interruption on one of them seriously affected the stability and uniform operation of the system, this old question came to the front for serious consideration.

With the advent of multiple or group units consisting of two or more generators, the time required to restore a unit to the system after once being disconnected from the bus, when not excited, would probably be not much less than an hour. This is because the two or more machines comprising the unit will retard at different rates and consequently will be so far out of synchronism that when the excitation of the various generators is reestablished, they will not pull into step. It therefore becomes necessary to allow the machines to come to rest, close the field circuits and accelerate in the usual way. Such an interruption on units of 50,000-kw. to 150,000-kw. capacity would obviously be most serious at the time of heavy load.

In order to establish a reasonably safe operating procedure for such emergencies and one that would reestablish normal conditions just as soon as possible, the authors have collected data on experiences and statements from various sources and have determined, by tests, the behavior of large units under this abnormal condition.

Replies from 10 operating companies and one manufacturer brought information about 16 cases in which field switches were reclosed without cutting the generator off the bus. No one reported any disturbance on the reclosing of the field. The authors have rather complete information on 18 other cases wherein the field circuits were reclosed without any difficulty.

OPINIONS OF OPERATING COMPANIES

Seven stated they had promptly reclosed the field switch or would not object to it being done.

Three stated they would not reclose the switch but would cut the generator off the bus.

One manufacturer of large units recommended the field switch be reclosed.

These statements concerned machines of from 8,000 kw. to 65,000 kw., both steam and hydro.

It is the practise in unattended hydroelectric plants to have the generators thrown onto the bus unexcited when about up to synchronous speed, after which the field is applied and the unit pulls into step.

The replies from operating companies probably represent the accumulated experience over a great many years and while probably not complete, no single case is cited wherein trouble resulted from reclosing the field circuit. It seems reasonable to conclude that where the general feeling is in opposition to such a practise, that had there been anything to support such a stand reference to it would have been made.

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[1] Electrical Asst. to Supt. of Generating Stations.

[2] Load Dispatcher, both of Commonwealth Edison Company, Chicago, Illinois.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

It would seem from some of the replies to the questionnaire that the behavior of unexcited generators is not very well understood, because several references are made to the anticipated danger of "pole slippage," "out-of-step," and "out-of-phase" conditions. In practically all cases of record referred to in answering the questionnaire and in 18 cases of which the authors have first hand information, the generators continued to carry load, sometimes they did not drop any, sometimes as much as 30 per cent but in all cases they carried some. This indicates that the generators did not drop below synchronous speed but probably went above speed and that pole slippage is of no moment. In the tests on the 60,000-kw. generator there is positive evidence that the rotors drifted ahead of synchronous speed and by different amounts. This was probably true in the other cases. It is therefore reasonable to believe that pole slippage as associated with possible complications incident to the opening of the field circuit is not harmful.

With the reestablishment of excitation the rotor poles build up slowly and as they do, the speed of the rotor changes slowly and the rotor and stator poles lock into step with properly related polarities.

The question of subnormal excitation of a generator has a bearing on this subject because of experience which indicates what the effect on a generator is when it slips a pole due to reversal of exciter polarity resulting from weak exciter field, etc. The point that should be borne in mind is, that the exciter should never be operated below the knee of its saturation curve. If it is, it may be overpowered by the induced voltage in the rotor circuit when the field switch is reclosed, causing the rotor poles to reverse as fast as they try to lock in with the stator poles. The harmful effect of such an occurrence on a large system is moderate as measured by bus voltage disturbance and apparently negligible in so far as harm to the generator. Aside from the remote possibility of accumulated dust and dirt being ignited by sparks from poor electrical joints in the steel structure of the rotor, no damage would be anticipated. No doubt, currents of high magnitude exist in the steel of the rotor at the time when the rotor speed differs from that of the armature poles.

Cases of this kind of disturbance and on units of 35,000 kw. have resulted in a 10 to 12 per cent dip in bus voltage and aside from a groan of the unit, did not interfere with parallel operation in the system.

As sub-normal excitation may allow pole slipping, this point was taken into consideration in the tests described below and normal setting of all rheostats maintained.

TESTS

Tests have been made on the restoration of the excitation of alternators of 30,000-kw., and 60,000-kw. capacity. Preliminary tests, four in number, made on the 30,000-kw. machine were more or less of a trial nature and served to show what the instrument set-up should be for the test on the 60,000-kw. multiple unit. Oscillograph records were not made but the observed indications of current, voltage, etc., were recorded. This unit was rated 35,000 kva., 85 per cent power factor, 12,000 volt, 1,200 r. p. m., 60 cycle; tandem compound, having 3.06 ohms synchronous impedance; no external reactance; operating in parallel with the Chicago system. The following readings were taken:

	Bus volts	Machine amperes	Machine kw.	Power factor
Before test	12,400	1,000	15,000	0.72 lag.
Field open	11,200	2,000–2,600	14,000–15,000	Off scale lead
After test	12,400	900	15,000	0.78 lag.

The field switch was left open for approximately one and one-half minutes on this test. The change in current and power factor after the field was reclosed was due to increase in excitation in other connected stations and on other generators in the same station while the field switch was open.

There was no violent fluctuation of current or voltage while the switch was open, the change from 1,000 amperes to 2,000 amperes was at a slow and approximately uniform rate covering about two seconds. The change from 2,000 to 2,600 amperes was irregular and without any definite frequency though observers agreed that it did seem as though average values might have a definite period.

A second test with the same set-up of values resulted in the same conditions. This was followed with a test when the unit was loaded to 21,000 kw. Results were about the same except the bus voltage dipped to 11,000—a 1,300-volt drop. After this test it was observed that the field discharge resistance was being heated. A voltmeter was then connected across the discharge resistance and a fourth test made which showed, by calculation, that the induced current in the field circuit was 100-120 amperes and fluctuating and reported "not to have dropped to zero at any time." This report is doubted.

Starting with a bus pressure of 12,400 volts, five seconds elapsed before the pressure dropped to 11,200 volts, going down at a slow and uniform rate. After the field switch was reclosed it took about one second for the exciter to build up the current to full value but took five seconds after that for the bus pressure to reach full value again.

The unit layout and instrument set up for the tests on the 60,000-kw. machine are shown in the accompanying diagrams.

This unit is of 60,000-kw. capacity, cross compound, 60 cycles, 12,000 volts. The high-pressure generator runs at 1,800 r. p. m., is of 17,000-kw. capacity and has a synchronous impedance of 5.8 ohms. The low-pressure generator is of 43,000-kw. capacity, 1,200

r. p. m., and has 1.92-ohms synchronous impedance. The external reactors between the unit and the bus are 827 kva., 3,500 amperes and have 3 per cent reactance on 12,000 volts.

During two preliminary tests the unit was given a load of 20,000 kw. at 85 per cent power factor. The switch was opened which cut off the excitation of both fields. The switch was left open for approximately three minutes, during which time the hand of the synchroscope made 16 revolutions, showing that the field of at least the high-pressure generator was slipping ahead of the system slowly. The speed of the high-pressure unit was compared with the system by means of the synchroscope which was connected between the house alternator on the high-pressure unit shaft and the 2,300-volt bus which was alive from the main 12,000-volt bus.

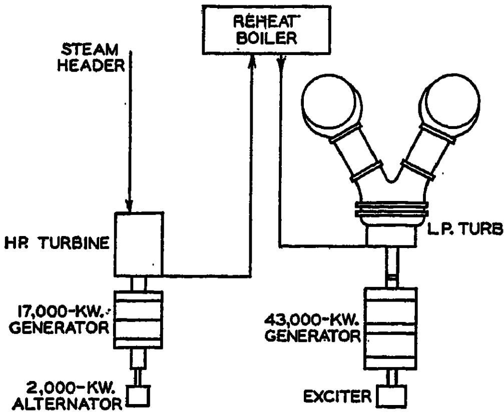

FIG. 1—CRAWFORD AVE. STATION

Plan of two-element 60,000-kw. turbo-generator unit No. 2. Commonwealth Edison Co. Feb. 28, 1930.

The reclosing of the field switch occurred about the time the synchroscope showed the high-pressure rotor to be 180 deg. out of phase. That is, the mechanical time-phase relation of the poles of the rotor was 180 deg. away from the normal position. There was a total absence of surging or violent fluctuations; the excess current on both generators simply subsided, the synchroscope needle stopped at the "in" phase position and the voltage came back to normal.

FINAL OSCILLOGRAPH TESTS

A second set of tests was run on the 60,000-kw. unit during which oscillograph records were made, but owing to the length of the films (24 ft.) only the important sections are given in the accompanying figures and these curves are faithful reproductions of the oscillograph record.

The field switch was opened three times in all. On the first test, the machine had 30,000-kw. load at unity power factor. A short, fast film was run to determine the proper scale on the oscillograph and the time relation between various waves.

On the second test the machine had the same load of 30,000 kw. at unity power factor but the field switch was kept open over 30 seconds while a 24-ft. oscillogram was taken. On the third test the machine had 50,000 kw. at 80 per cent power factor when the switch was opened. A 24-ft. film was again run for about 30 seconds.

The general performance of the machine in each test was similar but the amplitude of the current and voltage oscillations was much greater for the higher load. A plot has, therefore, been made for the latter case only, and root-mean-square values of current and voltage, instantaneous values of field current and speed have been shown.

A plan of the principal steam connections and another of the electrical connections used in the test, are also given.

OPENING THE FIELD

When the field switch was opened the field current immediately dropped to less than half value. Then for a period of four seconds the fields gradually became demagnetized. The station bus voltage dropped as the fields became demagnetized and the armatures gradually drew heavy magnetizing currents from the system.

From the end of the fourth second till the field switch was reclosed, generally transient conditions existed. Both machines ran considerably above synchronous speed and slipped past their regular pole positions many times. The speed of the high-pressure turbine was very erratic. Violent governor action was observed. The low-pressure turbine, not having a speed regulating governor, ran at a more uniform speed.

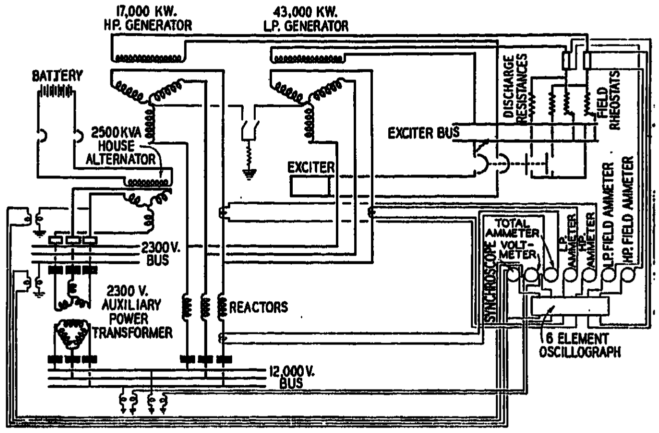

FIG. 2—CRAWFORD AVE. STATION

Two-element 60,000-kw. turbo-generator unit No. 2 instrument connections for open field test. Commonwealth Edison Co.

The steadiness in the speed of the low-pressure turbine can probably be accounted for by the fact that the reheat boiler served as a stabilizer for the rapidly pulsating steam that was passing through the high-pressure turbine. Since the heat in the reheat boiler was constant, it would momentarily give off more reheat to a smaller amount of steam at a lower pressure and less reheat to a larger amount at a higher pressure.

As the magnetic coupling between the field and armature poles was removed, the energy produced by the turbine being constant, the machine accelerated above synchronous speed. The field winding then cut lines of force and had induced in it a current which had a frequency proportional to the slip or the difference between armature and field speed. Its general characteristics were those of an induction generator.

As the turbine speeded up, the governor, set for a given load at synchronous speed, reduced the amount of steam into the turbine and the machine slowed down. When the machine approached synchronous speed, the governor opened up again. This cycle repeated itself very rapidly at high loads, much less rapidly at light loads.

When a field pole came under an armature pole it had induced in its winding a current which set up a magnetic pole of opposite polarity to that of the armature pole. Then as the field passed over to the next armature pole, the field pole became demagnetized and then remagnetized in the reverse direction. These reversing field currents are shown in Fig. 3 where they are plotted as instantaneous values.

The armature currents which are plotted as root-mean-square values, are seen to have a maximum and minimum value for each reversal of the field current. Ordinarily an induction generator would have constant armature current for a given speed. The peak values found on these tests can be explained by the fact that the field does not have a uniformly distributed winding such as would be found in the rotor of an induction machine. When the center of the field pole is not directly under the center of the armature pole, the field windings are not symmetrical with respect to the armature pole and it takes a larger armature current to induce the same field current than when the poles are centered.

The station bus voltage was reduced about 1,500 volts. This reduction was greatest when the armature currents were a maximum and was least when the armature currents were a minimum. The maximum armature currents checked very closely with predetermined values which were 2,100 and 6,000 amperes respectively for the high- and low-pressure generators.

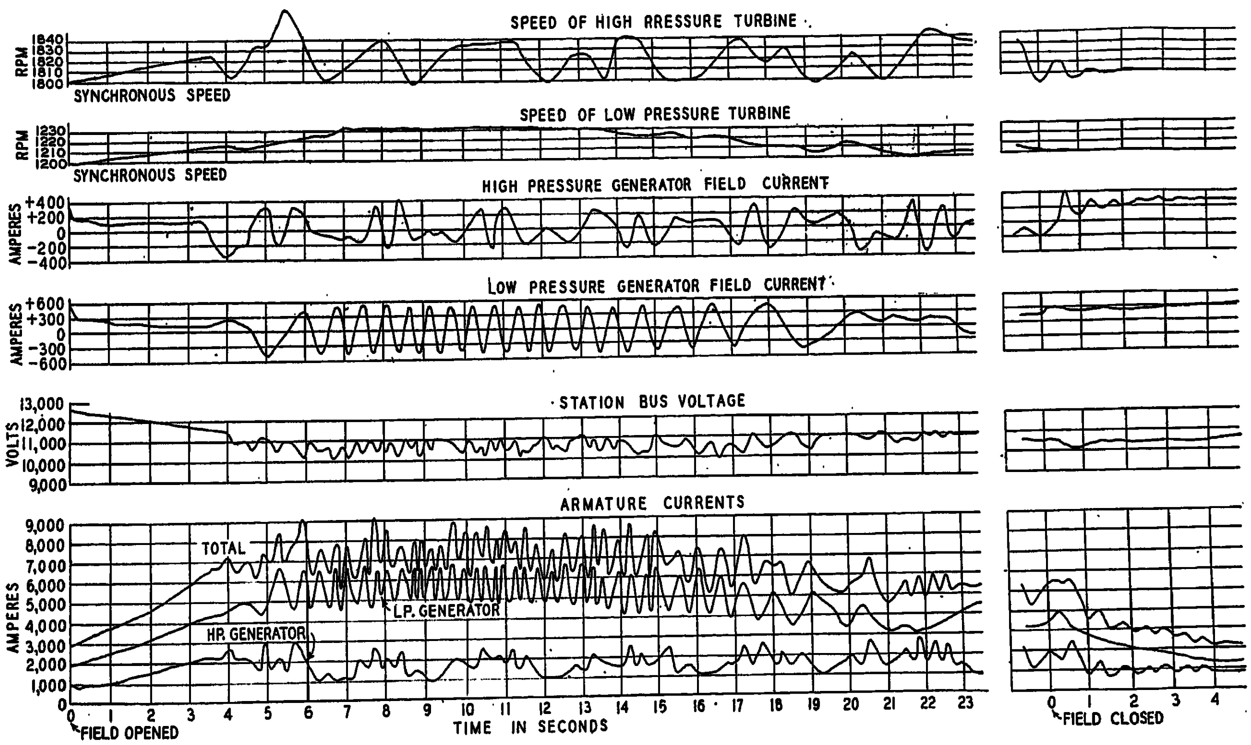

FIG. 3—GENERATOR OPENED-FIELD TEST

Unit 2—Crawford Ave. Station. Feb. 28, 1930. 60,000-kw. cross-compound turbine. Machine carrying 50,000 kw. at 80 per cent power factor when field switch was opened.

There is some question that if the field switch had been closed when the induced field current was a maximum in the reverse direction, the exciter (shunt wound) might have become demagnetized. In the worst case found here, the low-pressure field was found reversed 550 amperes and passed through a discharge resistance of 0.56 ohms so that the voltage which would have been thrown across the exciter would be 308 volts, only momentarily. This might have been enough to demagnetize an exciter set at 275 volts. It would also have been necessary for the high-pressure field current to be negligible or also reversed at the same time, since the net current in the common exciter is the instantaneous sum of the high- and low-pressure field currents.

It is thought that the time required to weaken and reverse the exciter would be greater than the duration of the induced field current at its maximum negative value. Therefore, the exciter would probably not be reversed.

The belief that excessive currents might be induced in the field winding which would prove injurious was not borne out by the observed values of current.

The tabulation which follows gives a comparison between the action on the two loads:

Load	30,000 kw.	50,000 kw.
High-pressure speed (max.)	1,855 r. p. m.	1,872 r. p. m.
Low-pressure speed (max.)	1,220 r. p. m.	1,233 r. p. m.
High-pressure field current (max. positive)	120 amperes	410 amperes
Low-pressure field current (max. positive)	180 amperes	550 amperes
Bus voltage (minimum)	10,500 volts	10,000 volts
High-pressure armature current (max.)	1,510 amperes	3,000 amperes
Low-pressure armature current (max.)	3,340 amperes	6,700 amperes

CLOSING THE FIELD

In each case when the field switch was closed, the field current instantly started to build up in the right direction although it had been reversed in one case just prior to the field being closed. The armature currents returned in about 5 seconds to their normal values and station voltage recovered to almost normal in about 5 seconds. The voltage, however, took about 20 seconds completely to recover.

The speed of the two generators, at the time of closing the switch, was not far from synchronism although it was not exactly synchronous. In each case the machine recovered in less than 2 seconds to its synchronous speed.

In the 30,000-kw. load test, the unit dropped a maximum of 30 per cent load and in the 50,000-kw. test, 40 per cent.

CONCLUSIONS

It is recognized that different types of generators behave in different ways when the excitation is cut off. Old units having low-resistance field windings and operating with 125-volt excitation are more erratic than later machines employing 250-volt excitation probably due to lower energy loss in the rotor. If the unit is carrying less than ¾ load, there is no danger in reclosing the field switch. If the unit is carrying more than ¾ load it will be prudent to lower on the governor before reclosing the field switch.

If the bus voltage has dropped to 60 per cent of normal it will be prudent to cut off the generator to prevent the possibility of other generators dropping out of step, but such a reduction in voltage due to an open field is unlikely on large systems.

Owing to its reactance, it is impossible for the rotor-field to snap up to full strength and correspondingly owing to a weaker magnetic coupling it is impossible for the rotor to change speed instantly, therefore, there can be no shock such as paralleling a machine out of phase.

Discussion

L. P. Shildneck: The proper procedure in case of accidental loss of excitation while under load has long been a moot question among operating companies. A critical study of this problem shows that no harm should result to the machine from re-closing the field switch. In fact, it reveals that the excitation should be re-applied as soon as possible to prevent damage to the rotor.

If viewed from the synchronization standpoint, this problem is considerably simplified. If the heating of the rotor is disregarded, any ordinary synchronous machine can be brought up to speed as an induction motor. At the instant before excitation, the machine is on the line at full voltage, with a stator current and power factor determined by the slip. After excitation, the rotor must speed up to synchronize with the stator flux wave. A turbine generator upon loss of excitation runs as an induction generator above synchronous speed at some slip determined by the governor setting. This condition is very nearly the same as the induction motor condition, since the machine is on the line at full voltage, with a stator current and power factor determined by the slip speed. Thus synchronization under this condition is actually easier than in the former case of an induction motor, for the rotor slows down to synchronous speed.

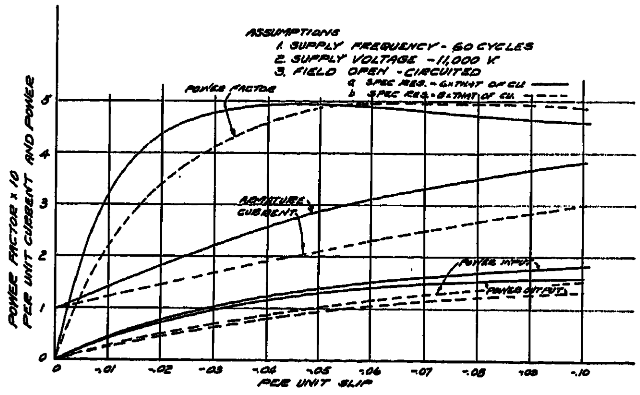

FIG. 1—INDUCTION GENERATOR CHARACTERISTICS

The induction generator characteristics of a solid turbine generator can be approximated by assuming that the rotor is a solid steel cylinder, with no slots or field copper. The rotor currents are mainly concentrated in a shell of about one-half inch depth on the outside periphery of the rotor. Curves of stator current, power factor, and power against slip are shown in Fig. 1, for various values of resistivity of rotor steel. These characteristics, together with the governor characteristics, shown in Fig. 2, then determine the operation of the set.

Referring to Fig. 3 of the paper, in the interval between 8 and 11 sec. after removal of excitation, the slip frequency, as observed from the low-pressure generator field current, is 1.83 cycles per sec., or the slip is − 0.03. According to the calculated induction generator characteristic curves, the stator current at 3 per cent slip is about twice normal, or nearly 5,000 amperes. This is seen to check the lower envelope of the L.P. generator armature current curve Fig. 3. The lower envelope constitutes a check point for the following reasons. There is one point in the cycle of operation of the rotor which justifies the assumption that the rotor was a solid cylinder with no slots or field winding. Consider now the actual rotor with a stator flux field revolving slowly around it. At one instant, the field coils are inductively related to the stator flux, and currents are induced in them. Ninety degrees later, the field coils are non-inductively related to the stator flux, and no current is induced in them. At the first instant, then, there are two parallel paths for rotor current to flow, one in the steel, and one in the copper. The impedance is then low. At the later instant, the field coils are "out of the circuit"; there is but one path, and that is in the steel. The impedance is then high. At this instant, current is flowing down one pole face and back along the adjacent one. Since the impedance is high, the stator current will be low. Thus the lower envelope of the armature current constitutes a check point for the calculations.

With the set carrying 50,000 kw. before loss of excitation, it is seen that the governor begins to throttle the steam as the speed rises above the system speed. Thus at 2 per cent overspeed the governor is admitting sufficient steam to carry approximately 30,000 kw. But at 2 per cent slip, the output of the generators is about half load, or 30,000 kw. Thus the set would finally settle down and carry a continuous load of 30,000 kw. However, the power factor is but 35 per cent, consequently the armature current is high, about 150 per cent of normal. While this condition for the stator is harmful, it will be seen that the rotor is in a worse plight.

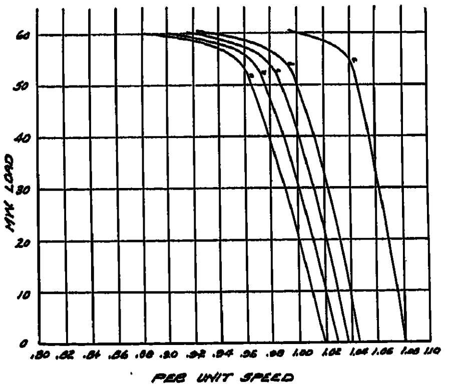

FIG. 2—GOVERNOR CHARACTERISTICS FOR VARIOUS GOVERNOR SETTINGS

An inspection of the test curves for armature current of the low-pressure unit reveals an interesting comparison between the values of currents flowing in the steel and in the copper portions of the rotor. These curves are but the effective current curves, or 0.707 times the envelope of the 60-cycle stator current. Notice that this effective stator current reaches a peak value of 6,500 amperes whenever the field coils are inductively related to the stator flux waves, and has a value of 5,000 amperes, whenever the field coils are non-inductively related (at 3 per cent slip). Thus the m.m.f. contributed by body or steel currents is proportional to 5,000, while the m.m.f. contributed by the copper currents is proportional to 6,500–5,000 or 1,500. The steel current m.m.f. is thus 3.33 times the m.m.f. set up by currents in the field copper (at 3 per cent slip). Herein lies the real danger in operating as an induction generator or motor for any length of time. The extremely high body currents concentrated in the outer shell of the steel rotor cause an intense heating of the rotor surface. Considerable damage may be done due to burning of the rotor wedges, especially at the ends of the rotor body. The extent of the danger is readily apparent from a consideration of the fact that at 2 per cent slip, the rotor losses are 2 per cent of the output of the machine. Normal full-load rotor loss is about ¼ per cent. Taking into account the fact that at 2 per cent slip, the load is but one-half normal, it is seen that the rotor loss is about 4 times normal when operating at 2 per cent slip. Furthermore, Fig. 2 shows that the slip is greatly increased when the machine loses excitation at full load. The sustained values will be: slip 4.5 per cent, load 85 per cent. Therefore, the rotor losses will be 0.85 x 4.5 per cent or 3.8 per cent as compared to a normal rotor loss of ¼ per cent. In other words, the rotor loss under this condition will be *15 times normal.* Moreover, this loss is not uniformly distributed over the periphery of the rotor surface; it is greatest at the ends of the machine where the current has to pass across the wedges. If heated sufficiently, these wedges may lose their physical strength to an extent which would allow them to be pushed out of the slots by the centrifugal force of the coils.

These are the dangers attending operation as an induction generator or as an induction motor. For these reasons, it is certainly inadvisable to operate any longer than necessary at other than synchronous speed. Excitation should be reestablished as soon as possible. If this cannot be done in very short order, the machine should be disconnected from the line immediately.

L. L. Perry: This discussion is particularly applicable to a triple compound unit comprised by one high-pressure generating unit and two low-pressure generating units. With this type of unit we have an installation wherein each low-pressure member can, when the high-pressure member is down, operate up to rated capacity by admitting high-pressure steam to the low-pressure turbines. In the event of accidental opening of the high-pressure generator field, the operator is confronted with two alternatives:

(1) He may at once open the main oil circuit breaker, cutting off the high-pressure generator from the bus and thereby lose that amount of generator capacity for many minutes. Meanwhile he can, in a few seconds, obtain the rated capacity of the two low-pressure generators by permitting high-pressure steam to enter the low-pressure turbines through the reducing valves provided therefor. (Indeed, this admission of high-pressure steam may be made automatic whenever the kilowatt load on the high-pressure turbine falls below a predetermined value.) In the first interim period the momentary loss to the system may be easily 90 to 100 per cent of the load carried by the total unit; 60 per cent may be restored in a few seconds, but it may require some minutes to restore the balance of 40 per cent of the load originally carried by the unit; or

(2) He may allow the high-pressure generator to operate on the system until he restores the field. In this case the momentary loss to the system may not exceed 50 to 60 per cent of the load carried by the total unit, and the restoration of the load previously carried may be made in much quicker time than the first interim period in the first alternative. Furthermore the loss of time necessary in the alternative to synchronize does not occur.

The facts presented in the paper permit the station electrical engineer to issue orders to the watch engineer that may easily prevent a serious disturbance to service.

L. E. Frost: There have been three occurrences at the Hudson Avenue Station which are of particular interest in connection with the paper by Messrs. Higgins and Wild. All of these involved the same machine, an 80,000-kw. cross-compound unit with generators of equal capacity on the two shafts.

The scheme of field current supply for this unit is shown in Fig. 3. The fields of the two generators are controlled through a duplex rheostat. The supply to both fields is derived jointly from a shaft exciter on the high-pressure unit, and from an excitation bus. Each of these sources of supply is controlled by an automatic air circuit breaker and reverse current relay.

In a period of one year, there were three occasions when this unit became unstable and pulled out of step while carrying loads ranging from 60,000 to 75,000 kw. Several plausible explanations have been advanced as to what started the disturbance in each case, but the proof has not been conclusive and my description of the sequence of events represents an opinion which is held by many who are familiar with the case, but which is not unanimous.

Whether the original disturbance was at the steam or at the electrical end of the unit, it seems clear that the unit pulled out of step and speeded up until the governor brought the steam input down to meet the output as an induction generator, at an unsteady speed corresponding (in its average) to a 61-cycle synchronous frequency. In each case the circuit breaker between the excitation bus and this unit opened automatically, and it appears that this was due to transient reversals of field current back into the excitation battery as the poles slipped past synchronous positions. As the unit had been drawing about a fourth of its excitation from the bus, the tripping of this breaker aggravated the disturbance by materially weakening the field supply. In each case the generator remained connected to the high-tension bus and in a minute or so pulled back into step. During this minute, the output of the machine fluctuated in fairly regular swings from 20,000 kw. up to 65,000 kw. or more at a slip frequency of about one cycle per second. At the same time the system voltage underwent swings of the same frequency but fortunately it did not reach serious values.

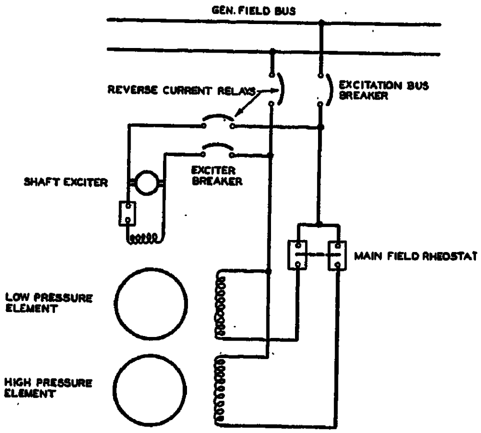

Fig. 3—Typical Generator Field Circuit Connections

At the first occurrence, which was in December, 1929, the controls of the machine were not touched by the operators until it had come back into synchronism of its own accord. At the second and third occurrences, which were in June and September of 1930, the operators increased the field current in order to force the unit back into synchronism. This step proved very effective. It was reported that as the field current was brought up the amplitude of load swings increased somewhat at first but that the unit quickly pulled into step and settled down to normal operation.

These cases are, of course, different from the situation presented by Messrs. Higgins and Wild, which was to apply field to a unit whose field current supply had been interrupted entirely; however, these experiences confirm in my mind the opinion that there is no inherent hazard in restoring normal field strength to an alternator which is out of step but still running somewhere near synchronous frequency.

D. D. Higgins: The thought the authors had in mind was not "what will happen if the field switch is opened," but rather "what will happen when it is closed." We know there is no reason for operating a generator unexcited and that there are very good reasons for not operating it so. At least there is one case in which the end wedges in the slots became overheated and were deformed by centrifugal force after some time. The rates of heating of various parts were carefully considered before the tests were made.

Inspection after the tests showed no visible defects had resulted during the tests lasting from one-half minute to three minutes.

The opening of a field switch is distinctly something the operating engineers do not want to happen, but which, nevertheless, does happen from time to time, possibly not oftener than once in five years.

These tests have given us information upon which we can confidently proceed to reduce immediately a case of major trouble to a simple operation and restore normal conditions in a minimum time.

Calculation of Synchronous Machine Constants—
Reactances and Time Constants Affecting Transient Characteristics

BY L. A. KILGORE*
Associate, A. I. E. E.

Synopsis.—Recent advances in the theory of synchronous machines have introduced a large number of new constants. The method of symmetrical components requires sequence reactances, and an accurate theory of transients requires transient and subtransient reactances and time constants. Most of the published discussion on the constants has been concerned with the application, rather than the calculation of values.

In this paper, all of the most significant constants are calculated, except the subtransient time constant. A general method of calculation is discussed in which the reactances are accurately resolved into components. Comparisons of test and calculated values are given. The formulas for salient-pole machines and turbine generators are given in Appendixes A and B.

The principle of superposition is applied to resolve accurately the reactances into components which can be readily calculated. The induced currents in the field and additional damping circuits are accounted for simply by applying the constant interlinkage theorem.

I. INTRODUCTION

UNTIL recently, the theory of synchronous machines has required relatively few constants. A single value of reactance, (usually called armature leakage) was used to calculate the initial short-circuit currents, and standard decrement curves used to determine the decay. Recent advances in theory have introduced a large number of new constants.

The method of symmetrical components[9] applied to single-phase, short-circuit calculations requires *negative-sequence reactance* (x_2) and *zero-sequence reactance* (x_o), as well as the positive-sequence reactances, which depend on the condition of application of current.

An accurate theory of transients[6] recognizes a subtransient (rapidly decaying component due to currents induced in additional damping circuits), as well as a transient component of symmetrical armature current. This requires several (positive-sequence) reactances, the *subtransient reactance* (x_d''), the *transient reactance* (x_d') and a *synchronous reactance* (x_d). The rate of decay of the transient components of current is determined by time constants. The time constant of the asymmetrical component is termed the *armature time constant* (T_a). The time constant of the rapidly decaying component of symmetrical current is the *subtransient time constant* (T_d''), and the time constant for the main transient component of current is the *transient time constant* (T_d').

As a reference, it is desirable to use the time constant of the field, which is called the *open-circuit transient time constant* (T_{do}').

A most complete solution[6,7] may require resolution of currents into a direct-axis component (reacting directly on the main field axis), and quadrature-axis component (reacting on the axis between poles). Where the constants are quite different in the two axes, this method requires *quadrature-axis constants:* (x_q, x_q'' *and in some cases* x_q', T_q' *and* T_q''), as well as the corresponding direct-axis constants (x_d, x_d'', x_d', T_d', and T_d''), described above.

These new methods consist essentially in resolving the actual currents and voltages into their essential components, and defining a sufficient number of constants to determine the initial and final values and the rates of decay. These constants have all been defined in other papers;[*,1,6,9] however, since the general method of defining the reactances is vital to the method of calculation, it is well to state it here. The reactance of a synchronous machine is the ratio of fundamental reactive armature voltage produced by the given component of armature current applied to the value of that component of current at rated frequency, and with the rotor running at synchronous speed.

These theories have been developed on the basis of no saturation, or at least assuming fixed permeability, but in practical calculations the effects of saturation cannot be neglected. These effects are most readily dealt with in most cases by modifying the constants. The effects of saturation on each of the constants is discussed in the companion paper[1]. It is shown that *for most practical purposes, only one value of each constant is necessary for a machine.* Except for the synchronous reactances and open-circuit time constant, the final values calculated will be the "saturated values," corresponding to the currents obtained on sudden short-circuit from full voltage.

Most of the published discussion of these constants has been concerned with the application, rather than the calculation of the values. However, all designers of large synchronous machines have had to meet this problem of calculating the constants, and those who use them are interested in how well they can be calculated.

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*Power Engineer, Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

9. For references see Bibliography.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

*Proposed definitions of these constants are included in a report of the Transmission and Distribution Committee of the A. I. E. E. This report, which was prepared by Prof. G. Dahl, will be presented at the Winter Convention, New York, N. Y., Jan. 25-29, 1932.

A recent paper[3] treats armature leakage reactance quite thoroughly, but does not cover the other constants. Another[4] describes an accurate method of treating synchronous motor constants by constructing a complete equivalent circuit. In this paper, formulas are developed for calculating the following constants: x_d, x_q, x_d', x_d'', x_q'', x_2, x_o, T_{do}', T_d' and T_a. This includes all of the more important constants, except the subtransient time constant ($T_a''T_d''$), which can be estimated from the test values given in the companion paper.[1] The quadrature transient reactance (x_q') is not included, since it is quite commonly assumed equal to x_d', in short-circuit calculations.

II. General Method of Calculation

To calculate any of the reactances as defined, it is only necessary to determine the flux produced by the component of current applied in the given manner, and to calculate the resulting armature voltage. The resultant field of flux may be complicated, but by applying the principle of superposition,[6] the resultant fields can be resolved into components which can be more readily calculated.

Components of Reactance. It is convenient to divide all the positive-sequence reactances into two components, one of which is the armature leakage (x_l) defined in a definite manner. The synchronous reactance is then the sum of the armature leakage and the reactance of armature reaction: $x_d = x_l + x_{ad}$ for the direct-axis, and $x_q = x_l + x_{aq}$ for the quadrature-axis. The reactance of armature reaction (x_{ad}) is defined as the reactance due to the space fundamental of air gap flux produced by the armature current acting alone.

The unsaturated transient reactance (x_{du}') is calculated as the sum of the armature leakage and an "effective field leakage" (x_F'): (x_F') is not the true leakage of the field with respect to the armature, but is a definite component of the total leakage of the armature with respect to the field. The saturated value of the transient reactance (x_d') is calculated by multiplying the unsaturated value (x_{du}') by an empirical constant (F_{st}), determined from test in the companion paper[1] as 0.88.

The subtransient reactance is calculated as the sum of the armature leakage and the "effective" damper winding leakage: $x_d'' = x_i + x'_{Dd}$, and $x_q'' = x_l + x_{Dq}'$. x_{Dd}' and x_{Dq}' are components of the total leakage of the armature with respect to the damper winding determined by assuming no net change of interlinkage with any of the damping circuits.

Armature Leakage Reactance Defined. Several recent writers[8] have treated armature leakage as an arbitrary component of the synchronous reactance. The definition might be stated as follows: The armature leakage reactance is the reactance due to the difference between the total flux produced by the armature current acting alone, and the space fundamental of the "flux in the air gap." To make this definition as useful as possible, the flux in the air gap will be understood to include the fringing flux at the ends which enters the rotor, since this is very nearly the component of the end leakage field which is mutual with the rotor circuits. For turbine generators with magnetic retaining rings, the end zone flux entering the retaining ring surface should be included in the end leakage, and not in the air gap flux.

Defined in this way, the armature leakage can be shown to be very accurately a component of all the positive-sequence reactances. This may be seen from the fact that the fundamental flux in the air gap is determined almost entirely by the space fundamental of the m. m. f., and that the remaining component consists only in slot and end leakage, and harmonic fluxes in the gap which are not appreciably affected by the condition of application of current. The effects of saturation on the armature leakage are generally negligible, except for the increased end leakage due to magnetic retaining rings in turbine generators.

Form of the Results and Formulas. The most useful forms for expressing the reactance coefficients are per cent and per unit, on a machine kva. base. In this paper, per cent notation is used, since this is the form most generally adopted when specifying the values of reactances. The time constants are given in seconds.

The reactance formulas must, of course, involve either directly or indirectly the armature turns, the frequency, and certain dimensions of the machine. The actual form of the equation makes considerable difference in the usefulness. Some writers have used the conception of effective permeance per unit length of slot, and others the permeance per phase belt per unit of length. In extending these conceptions to the calculation of all the reactances, it was found desirable to change the conception to a permeance per pole per inch of length, since the flux across the gap is most conveniently visualized as a flux per pole.

All the component reactances may be calculated as a product of a reactance factor (X), and a specific permeance (λ) for the given component, multiplied by flux distribution coefficients when necessary.

The specific permeance (λ) is defined as the effective flux per pole per inch of core length produced by unit ampere turns per pole.

The reactance factor (X) used here is a group of terms common to all the reactance formulas, but it is chosen in such a way as to have a definite physical significance. It is the per cent reactance for unit specific permeance, or the per cent of normal voltage induced by a fundamental flux per pole per inch numerically equal to the fundamental armature ampere turns at rated current.

The reactance factor can be written in several ways.

In terms of the turns, frequency and rated phase voltage and current, this factor can be shown to be:

$$X = 100\% \left(\frac{I_{ph}}{E_{ph}}\right) f\, l\, m\, p \left[q \left(\frac{n_s}{C}\right) k_p\, k_d \right]^2 10^{-8} \quad (1)$$

The factor can be expressed in terms of the ratio of effective ampere conductors per inch $(A\, k_p)$ to the fundamental air gap density (B_1):

$$X = 100\% \left(\frac{A\, k_p\, k_d}{\sqrt{2}\, B_1}\right) = 100\% \left(\frac{k_d}{\sqrt{2}\, C_1}\right) \left(\frac{A\, k_p}{B_g}\right) \quad (2)$$

This is very useful if the effective ampere conductors $(A\, k_p)$ and air gap density (B_g) are thought of as fundamental quantities in design, the ampere conductors per inch being a measure of current loading, and the air gap density a measure of the magnetic loading of the machine.

The chief advantages of this method are that it expresses the reactances as products of two factors, a specific permeance which involves only the proportions of the machine, and a reactance factor which is a simple function of the fundamental quantities of design. This makes it possible to see at a glance the effect of changing any of the proportions or factors. Also, it simplifies the work of calculation.

Calculation of Time Constants. The open-circuit time constant of the field may be calculated as the self inductance of the field (in henrys) divided by the field resistance in ohms:

$$T_{do}' = \frac{L_f}{R_f}.$$

The short-circuit transient time constant is calculated as:

$$T_d' = \left(\frac{x_d'}{x_d}\right) T_{do}'.$$

It is shown[1] that using the saturated value of x_d' in this relation gives a good approximation to the effective saturated value of T_d'.

The armature time constant (T_a) is the time constant of the asymmetrical component of armature current which is due to the flux trapped by the armature winding at the instant of short circuit. The effective reactance to the average asymmetrical current is the same as for negative-sequence current (x_2), and the resistance is the d-c. armature resistance (r_a) in per cent. Hence,

$$T_a = \frac{x_2}{2\, \pi\, f\, r_a}.$$

III. COMPARISON OF TEST AND CALCULATED VALUES

The formulas of Appendixes A and B have been checked by the numerous tests described in the companion paper.[1] Tables showing the tests and calculated values are given below. Most of the test values were obtained from special sudden short-circuit or locked tests, as indicated in the tables. The synchronous reactance (x_d) can be obtained from the commercial tests, hence a great many more checks on the synchronous constants have been obtained than those listed below. Also certain other special tests[1] were made to determine the effects of saturation, but will not be included here.

Table I gives the results of sudden short-circuit tests on salient-pole machines. Table II shows the results of locked tests obtained on other salient-pole machines with dampers, and Table III shows the results of similar tests on machines without dampers. Table IV shows the results obtained from sudden short-circuit tests on turbine generators.

TABLE I—CONSTANTS OF SALIENT-POLE MACHINES; COMPARISON OF TEST AND CALCULATED VALUES
Data from Three-Phase Short-Circuit Tests
All x's Are Per Cent Values — All T's Are in Seconds

Kva.		5,000	100	750	30,000	20,000	15,000	331	240	% error	
Kind		Gen.	Gen.	No damper H. W. G.	Cond.	Cond.	Cond.	Motor	Motor	Max.	Avg
Frequency		60	60	25	60	60	60	60	60		
Volts		7,600	2,300	6,600	5,000	11,000	11,500	440	2,200		
R. p. m.		900	1,200	187.5	720	720	900	1,200	277		
x_d	Test	90	125	120	150	160	165	160	105	6.8	3.6
	Calc.	90	130	115	160	170	170	160	110		
x_d'	Test	22	24	41	37	45	34	23	42	12.5	6.0
	Calc.	21.5	27	39	34	40	33	23	40		
x_d''	Test	13	16.5		19	27	21	16	32	11.0	8.0
	Calc.	14	15.0	40	21	30	19.5	15	30		
x_2	Test	13	17.0	62	18	26	20	16	33	8.0	5.0
	Calc.	13.5	16.0	57	19	28	19	16	33		
x_0	Test	6.3	3.30		7.20		11.0			33.0	18.0
	Calc.	5.5	2.20	15.0	8.40	13.5	11.0	9.3	18.5		
T_a	Test	0.095		0.180	0.130	0.210	0.180	0.033	0.048	38	16.0
	Calc.	0.100		0.200	0.180	0.250	0.160	0.030	0.040		
T_d'	Test	0.90	0.22		2.80		1.85			11.0	7.3
	Calc.	1.00	0.24	0.100	2.70	2.60	1.75		0.270		

TABLE II—CONSTANTS OF SALIENT-POLE MACHINES; COMPARISON OF TEST AND CALCULATED VALUES
Data from Locked Tests
All x's Are Per Cent Values
Machines With Dampers

Kva.		7,000	3,000	30,000	7,500	7,500	1,000	30,000	30,000	22,500	15,000	5,000	1,250	% error	
Kind		W.W.G.	W.W.G.	Cond.	Cond.	Cond.	Cond.	Motor	Cond.	Cond.	Cond.	Cond.	Cond.		
Frequency		60	50	60	60	60	60	50	60	60	60	60	60	Max.	Avg.
Volts		6,600	6,600	13,600	4,800	4,000	2,300	11,500	5,000	12,500	11,950	12,470	480		
R. p. m.		450	750	720	720	900	900	600	720	300	900	900	1,200		
x_d	test	97	160	170	175	145	160	78	170	120	155	170	190	6.3	2.0
	calc.	96	160	170	180	150	160	80	170	120	165	175	200		
x_d''	test	26	16.5	23	24	21	18	13	20	29	20	27	23	7.5	4.6
	calc.	25	17.0	24	23	20	18.5	13	21	27	18.5	25	22		
x_2	test	25	16	20	23	19	16	12	18	28	19	27	22	10.0	3.7
	calc.	23	16	22	22	19	17	12	18.5	27	18.5	25	22		
x_o	test	14.5	3.60	11.0	12.0	3.0		3.0	7.2	15.5	3.1	4.4		31.7	12.5
	calc.	13.5	3.45	11.5	13.0	2.45	6.55	3.95	8.2	18.0	2.8	3.9	8.0		

TABLE III—CONSTANTS OF SALIENT-POLE MACHINES; COMPARISON OF TEST AND CALCULATED VALUES
Data from Locked Tests
Machine Without Dampers

Kva.		13,750	7,000	4,250	2,330	30,000	187	730	% error	
Kind		W.W.G	W.W.G.	W.W.G.	W.W.G.	Gen.	Gen.	Motor		
Frequency		60	50	60	50	60	60	60	Max.	Avg.
Volts		6,600	6,600	2,300	6,600	11,500	240	2,300		
R. p. m.		90	94	600	125	600	200	1,200		
x_d	test	110	115	135	115	115	94	130	4.2	1.8
	calc	110	120	135	115	120	94	135		
x_{du}''	test	43	44	37	45	33	41	30	6.0	2.5
	calc	44	43	38	44	35	42	30		
x_2	test	58	61	62	65	58	55	55	10.3	4.5
	calc	57	60	60	60	52	57	53		
x_o	test	25	24		24	9.3			10.4	5.7
	calc	25.5	23.5		21.5	8.5				

TABLE IV—CONSTANTS OF TURBINE GENERATORS; COMPARISON OF TEST AND CALCULATED VALUES
Data from Three-Phase Short-Circuit Tests
All x's Are Per Cent Values All T's Are in Seconds

Kva.		7,500	8,575	9,375	12,500	18,750	43,750	68,750	75,000	% error	
Frequency		60	60	60	60	60	60	60	60		
Volts		6,600	4,150	6,600	11,000	13,800	13,800	13,200	11,600	Max.	Avg.
R. p. m.		3,600	3,600	3,600	3,600	3,600	1,800	1,800	1,800		
x_d	test	120	96	110	100	115	130	97	110	2.0	0.6
	calc	120	97	109	98	116	130	97.5	110		
x_d'	test	16.5	12	14	13.5	14	25	21	24	10.8	4.1
	calc	16.0	12	13	13.0	15.5	26	21	23		
x_d''	test	9.2	8.4	7.5	8.8	8.5	17	12	14	14.4	7.4
	calc	9.6	7.2	8.1	7.9	8.1	16	13	14.5		
x_o	test	1.80	1.60	1.60		3.1	5.1	5.9	10.0	18.7	7.1
	calc	1.95	1.50	1.30		2.7	5.0	5.9	9.8		
T_a	test	0.043	0.11	0.085	0.11	0.13	0.28	0.25	0.26	53.3	17.4
	calc	0.066	0.11	0.086	0.105	0.12	0.23	0.31	0.34		
T_d'	test	0.56	0.44	0.49	0.54	0.59	1.00	1.60	1.60	16.4	8.0
	calc	0.48	0.415	0.41	0.55	0.57	1.10	1.70	1.70		

It will be seen that the agreement between test and calculated values is quite good, except that in a few cases where the value of the zero-sequence reactance is quite small the per cent error is fairly large. Also, the calculated value of armature time constant in a few cases is considerably higher than the test value. This may possibly be due to external resistance in the armature circuit or breaker contacts, for the armature resistance is so low that a very little external resistance will appreciably affect the time constant.

IV. CONCLUSIONS

A general method has been given for calculating the constants of synchronous machines affecting the transient characteristics. In Appendixes A and B formulas have been given for all the more important constants, except the subtransient time constant. Comparison of test and calculated values shows that they give sufficiently good results over a wide range of types and sizes.

The formulas are based on a physical conception of the actual currents and flux fields involved. An attempt has been made to obtain simple formulas for design calculations, and still retain all the most significant factors, so that the formulas will cover a wide range of types and sizes of machines. The formulas are definitely limited to the usual two-layer type of winding. Only laminated-pole salient-pole machines, and solid rotor turbine generators are considered. The methods used can readily be extended to cover other special cases.

The general method of resolving the reactances into components has advantages both in calculating and in visualizing the flux fields involved. The method of expressing the component reactances as a product of a reactance factor, and specific permeances and flux distribution coefficients for the several components, has been found very useful.

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Appendix A—Formulas for Salient-Pole Machines

I. ARMATURE LEAKAGE REACTANCE (x_l)

Slot Leakage. Complete formulas have been given[8] for calculating slot leakage, derived by assuming the flux to go straight across the slot. With good approximation, Mr. Alger showed that the "slot constant" (effective permeance per cm. of slot) could be calculated as

$$k_x \left(\frac{h_2}{b_s} + \frac{h_1}{3\,b_s} \right),$$

and k_x could be determined as

$$\frac{1}{4} \left(\frac{3\,y}{m\,q} + 1 \right)$$

for three-phase, and as $\left(\frac{y}{m\,q} \right)$ for two-phase.

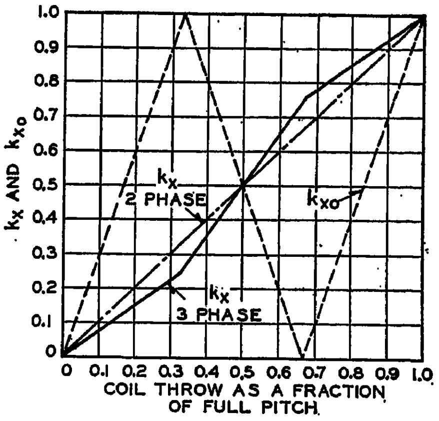


FIG. 1—REDUCTION OF SLOT REACTANCE DUE TO CHORDING

k_x = factor for positive- and negative-sequence reactance
k_{xo} = factor for zero-sequence reactance

These results expressed as a specific permeance give:

$$\lambda_s = C_x \frac{20}{m\,q} \left[\frac{h_2}{b_s} + \frac{h_1}{3\,b_s} \right],$$

where

$$C_x = \frac{k_x}{k_p^2\,k_d^2}.$$

See curves of Figs. 1 and 2.

Tooth Tip and Zig-Zag Leakage. In the paper referred to above, formulas were given for belt and zig-zag leakage, due to flux produced across the gap by the harmonics of armature m. m. f., but these did not include any increase in leakage due to flux going from tooth to tooth. In the following development, the principle of superposition is used to establish an accurate basis for calculating all of these components.

The total resultant field of flux, (within the core length) produced by the armature current may be accurately resolved into components produced by two imaginary sets of currents which, when superposed, give only the real current. The first component is due to a set of currents flowing on the armature surface, each uniformly distributed over a slot pitch and equal to the current in the slot; the second component is that due to a set of currents flowing in the conductors and returning uniformly distributed over the slot pitch. The m. m. f. due to the first set of imaginary currents may be analyzed as a fundamental and harmonics. The fundamental of this m. m. f. produces the fundamental flux; and the harmonics produce the belt leakage, which is due to the concentration in a finite number of phases. The second set of currents produces the slot, tooth tip and zig-zag leakage fields. The $\frac{b_t}{\tau_s}$ portion of the current of one slot, which returns over a half tooth width on each side, produces a field as shown in Fig. 3.

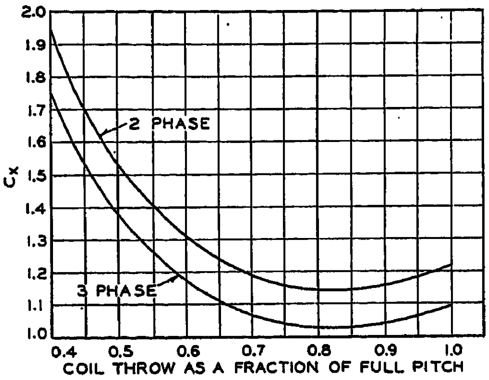


Fig. 2—Slot Leakage Factor (C_x)

A number of such plots shows that the effective permeance per cm. of slot (not included in the slot leakage) may be approximated as

$$\left[\frac{b_t^2}{8\,\tau_s\,g} + 0.35\,\frac{b_t}{\tau_s}\right].$$

Using an average value of $\frac{b_t}{\tau_s} = 0.56$, it reduces to

$$\left(0.2 + 0.07\,\frac{b_t}{g}\right).$$

This includes the tooth tip and the so-called zig-zag leakage.

It is convenient to calculate a specific permeance λ_i for the slot tooth tip and zig-zag leakage combined:

$$\lambda_i = C_x \frac{20}{m\,q}\left[\frac{h_2}{b_s} + \frac{h_1}{3\,b_s} + 0.2 + .07\,\frac{b_t}{g}\right] \quad \text{(1a)}$$

Belt Leakage. As defined, the belt leakage is due to the harmonics of armature m. m. f., determined by uniform current distribution. For a full pitch winding, where the slots per pole per phase (q) are integral and large, the reactance calculated by summing up the harmonics[8] can be shown to be 0.002 x_{ad} for three-phase, and 0.015 x_{ad} for two-phase. (This was derived assuming a uniform gap and no damping.) For a smaller number of slots, these formulas are not very accurate, but they are sufficiently good since the value is small. The case of fractional slots per pole is difficult if a complete solution is desired. However, the unbalance in m. m. f. resulting from fractional slots is kept to a minimum, and the additional reactance may be neglected in normal machines.

Expressing these results as a specific permeance, and assuming that the two-phase leakage varies with chording in the same way as that part which is due to the third harmonic:

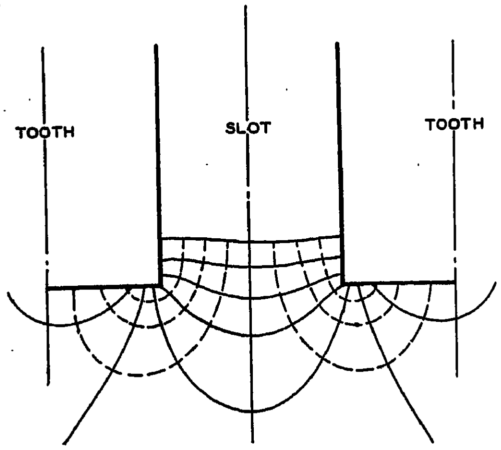


Fig. 3a—Tooth Tip Leakage Field Due to Differential Current—Large Air Gap

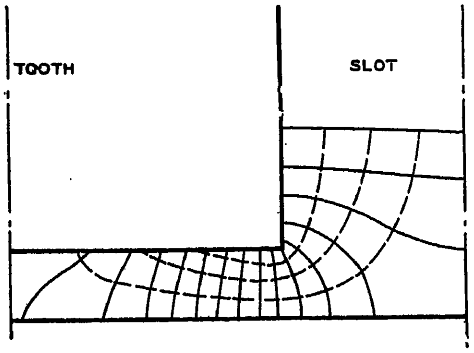


Fig. 3b—Tooth Tip Leakage Field Due to Differential Current—Small Air Gap

$\lambda_B = 0$ (negligible) for three-phase;

$$\lambda_B = 0.095\,\frac{d}{p\,g'}\left[\frac{\sin\frac{3\,y\,\pi}{m\,q\,2}}{k_p}\right]^2 \text{for two-phase} \quad \text{(2a)}$$

End Winding Leakage. The end leakage formula presented here is essentially the same as that developed by Mr. B. G. Lamme. Professor Alfred Still has recently published a paper[2] in which he develops a formula on the same basis.

The method referred to consists in treating the end winding leakage as a revolving field in air. The presence of the iron is neglected in the derivation and, if necessary, an empirical correction is applied to the result. Both Messrs. Lamme and Still assumed that the flux went from pole to pole without spreading out axially. Further, in order to integrate the flux, each assumed that the flux paths were arcs of circles.

This method of analysis can be carried one step further by using the exact solution[8] for a sinusoidal m. m. f. distribution in air, assuming a two-dimensional field. The exact solution gives the very simple result that the field is sinusoidally distributed, and the flux per pole per inch is 3.19 times the fundamental ampere turns.

The pitch of the winding for the straight coil extension (l_{e2}) is the same as for the gap, but it drops off to zero at the end of the coil. An effective length 1/2 (l_{e1}) will be used as in Lamme's formula.

The end winding field is not truly a two-dimensional field as assumed, but spreads out axially. This effect was investigated further by making approximate plots of the three-dimensional field in the several views. The increased leakage due to local flux closing about the individual conductors was calculated by resolving the field into components in a manner similar to that described for the tooth tip leakage. It was found that these factors, although small, are not negligible, and may be approximately accounted for by a constant factor 1.25.

Expressed as a specific permeance, the end winding leakage is (1.25) . (3.19) times the ratio of effective end winding extension on both ends, to the core length

$$\lambda_e = 4/l\ (2\ l_{e2} + l_{e1}) \tag{3a}$$

The armature leakage reactance is calculated as the product of the reactance factor (X) determined by equation (1) or (2), and the specific permeances, equations (**1a**), (**2a**), and (**3a**).

$$x_l = X(\lambda_i + \lambda_e + \lambda_B) \tag{4a}$$

II. Reactances of Armature Reaction (x_{ad}, x_{aq}) and Synchronous Reactances (x_d, x_q)

The specific permeance of the air gap (λ_a) is most conveniently determined on the assumption that the gap is uniform, and the actual flux distribution may be calculated by the use of flux distribution coefficients given below. The effective gap (g') is determined by multiplying the actual gap (g) by Carter's coefficients for stator slots and vents, and by a reduction factor for end fringing flux.

$$\lambda_a = 3.19 \left(\frac{2\,d}{p\,g'} \right) \tag{5a}$$

The flux distribution coefficients used here are defined as follows: *C_1 is the ratio of the fundamental to the actual maximum value of the field form.* (The field form is the wave of flux density due to the field only.) *The "pole constant" (C_p) is the ratio of average to maximum of the field form. The ratio of equivalent field to armature ampere turns (C_m) is the ratio of fundamental air gap flux produced by the fundamental of armature m. m. f. to that produced by the field for the same maximum m. m. f. C_{d1} is the ratio of the fundamental air gap flux produced by the direct-axis armature current to that which would be produced with a uniform gap equal to the effective gap over the pole center. C_{q1} is the corresponding coefficient for the quadrature-axis.*

All of these coefficients may be determined by accurate flux maps, but it is often more convenient to use formulas, except for C_p and C_1. These two constants are determined directly or indirectly in almost any design procedure, by laying out the field form either from a flux map or other accurate method.

A formula for C_m may be derived assuming the flux to go straight across a uniform gap over the pole face. The formula is much more accurate than might appear from the assumptions stated, since the fringing and increase in gap at the pole tip affect both quantities in the ratio about equally. This formula was checked by accurate flux plots on a wide range of pole shapes from 4 to 88 poles.

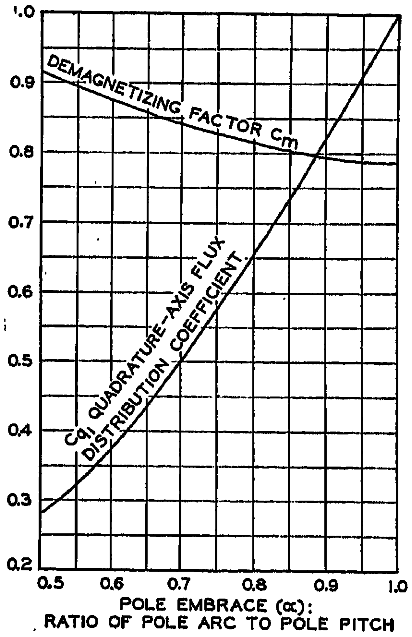


Fig. 4—Flux Distribution Coefficients for Salient-Pole Machines C_m and C_{q1}

$$C_m = \left(\frac{\alpha\,\pi + 4 \sin \alpha\,\pi}{4 \sin \alpha \dfrac{\pi}{2}} \right) \tag{6a}$$

Where α is the pole embrace. See curve, Fig. 4.

From the definition of C_m, it may be seen that $C_m = C_{d1}/C_1$. Having determined C_m and C_1 as described above,

$$C_{d1} = C_m\,C_1 \tag{7a}$$

An approximate formula for C_{q1} may be derived on the assumption that the flux goes straight across a uniform gap over the pole face.

$$C_{q1} = \left[\alpha - \frac{\sin \alpha \pi}{\pi} \right];$$

making some allowance for end fringing and an average increase in gap at the pole tips, a modified formula was obtained which checked sufficiently well with the series of flux plots mentioned.

$$C_{q1} = \left[\frac{4 \alpha + 1}{5} - \frac{\sin \alpha \pi}{\pi} \right] \qquad \textbf{(8a)}$$

The flux distribution coefficients which have been designated here as C_1, C_{d1} and C_{q1} can be calculated for a particular pole shape from the curves given in a paper[10] by R. W. Wieseman.

Reactances of armature reaction may be calculated as:

$$x_{ad} = X\, C_{d1}\, \lambda_a \qquad x_{aq} = X\, C_{q1}\, \lambda_a \qquad \textbf{(9a) and (10a)}$$

As an alternate method: x_{ad} may be calculated from the gap ampere turns M_g and the demagnetizing ampere turns ($M_m = C_m M_A$).

$$x_{ad} = 100\% \frac{M_m}{M_g} \qquad x_{aq} = \frac{C_{q1}}{C_{d1}} x_{ad} \qquad \textbf{(11a) and (12a)}$$

Synchronous reactances are calculated simply as the sum of armature leakage and reactances of armature reaction:

$$x_d = x_l + x_{ad} \qquad x_q = x_l + x_{aq} \qquad \textbf{(13a) and (14a)}$$

III. FIELD LEAKAGE AND TRANSIENT REACTANCE

The transient reactance is actually the total leakage of the armature with respect to the field (assuming no additional damping circuits). As explained in Section II of the paper, it will be calculated as the sum of two arbitrary components, the armature leakage (x_l) and an effective field leakage (x_F').

The specific permeance for field leakage (λ_F) will be the side and end leakage flux per pole per inch for unit field ampere turns. The side leakage flux per inch may be determined accurately by a flux map for the field only, similar to those shown in Fig. 1 and Fig. 50 in a series of articles[6] by J. F. Calvert. Each element of flux is multiplied by the fractional part of the turns linked.

It is often more convenient to use an approximate formula. The following formula was derived assuming that the flux goes straight across the interpolar space (at right angles to the center line between poles), except near the armature surface where the flux is assumed to go straight across half way from the pole head to the center line between poles, and then to spread out so that the upper boundary intersects the armature surface and the center line between poles at 45 deg., as it should theoretically. A further correction was made to allow for the shortening of the path of part of the flux which terminates on the under side of the pole tips.

The *side leakage* expressed as a specific permeance based on the above assumptions is:

$$\lambda_{Fs} = (3.19)\, \frac{4}{3} \left[\frac{3\,(h_h + g - .055\, \tau_r)}{(\tau_r - b_h)} + \frac{h_{f1} + 3\, h_{f2} + 0.1\, \tau_r \left(1 - \frac{10}{p}\right)}{\frac{\pi}{p}\,(d_r - 2\, h_h - 0.4\, h_{f1}) - b_p} \right] \qquad \textbf{(15a)}$$

This may appear rather long, but it will be noted that it is expressed directly in the main dimensions of the pole, and does not require a pole layout. This formula was found to check well with the results obtained by flux maps on a wide range of pole shapes for machines from 4 to 88 poles.

To determine the end leakage field, a number of two-dimensional flux plots was made in two views, which show the flux which fringes from pole to pole and the flux which closes about the field coil ends. The resultant field is obviously not two dimensional, but an approximate formula based on these plots should be sufficiently accurate.

$$\lambda_{Fe} = 3.19 \left[\frac{4(l_h - l) + 2\, h_{f1} + 0.5\, b_p}{l} \right] \qquad \textbf{(16a)}$$

The specific permeance for the effective pole leakage is:

$$\lambda_F = \lambda_{Fs} + \lambda_{Fe} \qquad \textbf{(17a)}$$

The effective field leakage reactance (x_F'), which added to armature leakage (x_l) gives the transient reactance, may be calculated as follows: With unit fundamental armature ampere turns suddenly applied on the direct-axis, an initial field current (I_f) will be induced of such value that the net interlinkage with the field produced by both the armature and field currents is zero. The interlinkage (per inch) produced by the armature current is

$$\left(\frac{\pi}{4}\, C_1\, \lambda_a\right) N_p,$$

and by the field current

$$N_p\, I_f \left(\frac{\pi}{2}\, C_p\, \lambda_a + \lambda_F\right) N_p;$$

hence

$$N_p\, I_f = \left[\frac{\frac{\pi}{4}\, C_1\, \lambda_a}{\frac{\pi}{2}\, C_p\, \lambda_a + \lambda_F} \right]$$

The net fundamental air gap flux (per inch) produced by both armature and field is then

$$\left[C_{d1}\,\lambda_a - \frac{\frac{\pi}{4}\,C_1^2\,\lambda_a^2}{\frac{\pi}{2} C_p\,\lambda_a + \lambda_F} \right]$$

The effective field leakage is:

$$x_F' = X\left[C_{d1}\,\lambda_a - \frac{\frac{\pi}{4}\,C_1^2\,\lambda_a^2}{\frac{\pi}{2} C_p\,\lambda_a + \lambda_F} \right]$$

$$= x_{ad}\left[1 - \frac{\frac{\pi}{4}\,\frac{C_1}{C_m}}{\frac{\pi}{2}\,C_p + \frac{\lambda_F}{\lambda_a}} \right] \qquad (18a)$$

The unsaturated value of transient reactance is:

$$x_{du}' = x_l + x_F' \qquad (19a)$$

The saturated transient reactance (x_d') is determined by multiplying by an empirical factor (F_{st}). The test results described in the companion paper[1] indicate that this factor may be taken as a constant $F_{st} = 0.88$, with sufficiently good results on normal machines.

$$x_d' = F_{st}\,.\,x_{du}' \qquad (20a)$$

IV. DAMPER WINDING LEAKAGE (x_{Dd}', x_{Dq}') AND SUBTRANSIENT REACTANCES (x_d'', x_q'')

The initial flux set up by suddenly applied direct-axis armature current is limited by the damper winding. The flux maps of this field were constructed on the assumption that there is no net change of interlinkage with any of the damper winding circuits. The field is quite complicated, but it was found that the fundamental flux could be calculated with fair approximation from the permeances of the main parts of the flux paths. Approximately

$$\left[\cos \frac{(n_b - 1)\,\tau_b}{\tau_r}\,\frac{\pi}{2} \right]$$

part of the armature m. m. f. acts across the field, leakage permeance (λ_F) in series with the permeance of the end damper bar (λ_b) combined in parallel with the permeance of the gap over the pole tip (λ_{pt}).

$$\lambda_b = 6.38\left(0.5 + \frac{h_{b2}}{b_{b2}} + \frac{h_{b1}}{3\,b_{b1}} \right) \qquad (21a)$$

Where 0.5 is an approximation to the tooth tip permeance per cm. of damper slot. For round bars, use 0.62 instead of $\dfrac{h_{b1}}{3\,b_{b1}}$.

Using an average increase in gap at the pole tip:

$$\lambda_{pt} = 6.38\left[\frac{b_h - \tau_b\,(n_b - 1)}{3\,g'} \right] \qquad (22a)$$

Although the flux is not sinusoidally distributed under these conditions, the distribution is such that the total flux is a good approximation to the fundamental. Combining these permeances and multiplying by the fractional part of the ampere turns acting, the resultant formula for the specific permeance is:

$$\lambda_{Dd} = \left[\cos \frac{(n_b - 1)\,\tau_b}{\tau_r}\,\frac{\pi}{2} \right] . \left[\frac{(\lambda_b + \lambda_{pt})\,.\,\lambda_F}{\lambda_b + \lambda_{pt} + \lambda_F} \right] \qquad (23a)$$

$$x'_{Dd} = X\,\lambda_{Dd} \qquad (24a)$$

The direct-axis subtransient reactance (x_d'') of a machine with a damper winding is calculated as the sum of the components (**4a**) and (**24a**):

$$x_d'' = x_l + x_{Dd}' \qquad (25a)$$

For a machine without dampers:

$$x_d'' = x_d' \qquad (26a)$$

The quadrature-axis damper leakage is determined on the same base. In this case, the flux goes tangentially down the gap and across the damper bar slots. The effective permeance per cm. for one slot is

$$\left[0.5 + \frac{h_{b2}}{b_{b2}} + \frac{h_{b1}}{3\,b_{b1}} + \frac{g}{\tau_b} \right].$$

The part of the fundamental ampere turns acting across one slot is

$$\left(\pi\,\frac{\tau_b}{\tau_r} \right),$$

and the flux is very nearly sinusoidally distributed; hence,

$$\lambda_{Dq} = \frac{20\,\tau_b}{\tau_r}\left[0.5 + \frac{h_{b1}}{3\,b_{b1}} + \frac{h_{b2}}{b_{b2}} + \frac{g}{\tau_b} \right] \qquad (27a)$$

In this case, the dimensions of the slot and bar in the pole center should be used. The effective damper winding leakage is:

$$x_{Dq}' = X\,\lambda_{Dq} \qquad (28a)$$

The quadrature-axis subtransient reactance (x_q'') for machines with dampers is calculated as the sum of the components (**4a**) and (**28a**):

$$x_q'' = x_l + x_{Dq}' \qquad (29a)$$

For machines without dampers (**12a**) or (**14a**):

$$x_q'' = x_q \qquad (30a)$$

V. NEGATIVE SEQUENCE (x_2)

As explained in Section II, the negative sequence reactance may be calculated as the average of the subtransient reactances.

$$x_2 = \frac{1}{2}\,(x_d'' + x_q'') \qquad (31a)$$

VI. ZERO-SEQUENCE REACTANCE (x_o)

Since the zero-sequence currents are all in phase, the fundamental m. m. fs. of the three phases cancel out, and there is no appreciable fundamental flux across the gap. Hence, it consists in a slot and belt leakage, with a small belt leakage in the end windings. Mr. Alger[8] has derived a factor for the effect of chording on zero-sequence slot reactance. This factor will be designated here as k_{xo}. See curves, Fig. 1. The specific permeance for slot and tooth tip leakage can be shown to be:

$$\lambda_{io} = \left[\lambda_i \left(\frac{k_{xo}}{k_x} \right) + \left(\frac{20}{m\, q\, k_p^2\, k_d^2} \right) \left(\frac{h_1 + 2\, h_3}{12\, b_s} \right) \right] \tag{32a}$$

For machines with a damper winding, the belt leakage flux over the pole face is restricted in the same manner as the quadrature subtransient reactance flux. Neglecting the reluctance of the flux path across the gap, the specific permeance for a full pitch winding would be λ_{Dq}, equation (27a). Since this leakage varies with the throw in very nearly the same manner as the slot leakage, it may be written:

$$\lambda_{Bo} = \left(\frac{k_{xo}}{k_x} \right) \lambda_{Dq} \tag{33a}$$

For machines with no dampers, the effective permeance per cm. of phase belt would be $\frac{\tau}{36\, g'}$, if the winding was full pitch and the gap was uniform. Expressed as a specific permeance, this would be

$$\frac{20}{m\, k_d^2} \left(\frac{\tau}{36\, g'} \right) \cong 0.1\, \lambda_a,$$

but it should be reduced by about 0.7 for an average pole embrace. To take into account chording, it may be multiplied by $\left(\frac{k_{xo}}{k_p^2} \right)$. Hence, for machines with no damper winding:

$$\lambda_{Bo} = \frac{k_{xo}}{k_p^2} (.07\, \lambda_a) \tag{34a}$$

In the end windings, the fundamental m. m. fs. cancel, but the local flux about the phase belt is equivalent to about 0.2 of the positive sequence end winding leakage. The zero-sequence reactance will be calculated as the sum of the slot, belt, and end leakage components:

$$x_o = X(\lambda_{io} + \lambda_{Bo} + 0.2\, \lambda_e) \tag{35a}$$

VII. TIME CONSTANTS (T_{do}'), (T_d'), (T_a)

The self inductance of the field in henrys is

$$L_f = N_p^2\, p\, l\, 10^{-8} \left(\frac{\pi}{2} C_p\, \lambda_a + \lambda_F \right).$$

As explained in Section II, the open-circuit time constant may be calculated as a ratio of L_f to the resistance of the field (R_F); the resistance (R_f) should be the value in ohms at 75 deg. cent.

$$T_{do}' = \frac{L_f}{R_f} \tag{36a}$$

The unsaturated value of the (short-circuit) transient time constant can be shown to be exactly

$$\left(\frac{x_{du}'}{x_d} \right) T_{do}'.$$

Tests[1] show that a good approximation to the saturated value may be had by assuming the transient time constant to be reduced by the same factor as the transient reactance; hence:

$$T_d' = \frac{x_d'}{x_d} T_{do}' \tag{37a}$$

The armature time constant may be calculated as explained in Section II:

$$T_a = \left(\frac{x_2}{2\, \pi\, f\, r_a} \right) \tag{38a}$$

Where r_a is the d-c. armature resistance in per cent at 75 deg. cent.

Appendix B—Formulas for Turbine Generators

Due to the differences in construction, many of the formulas for turbine generators are different from those for salient-pole machines, but most of the conceptions involved are the same. Hence, only the differences in the formulas will be discussed.

I. ARMATURE LEAKAGE (x_l)

The reactance of armature reaction of turbine generators is calculated by assuming the flux to go straight across the gap. Therefore, it is necessary to include the fundamental flux going tangentially in the gap as a part of the armature leakage. This component is most conveniently accounted for by adding $\frac{g}{2\, \tau_s}$ to the permeance per cm. of slot. The specific permeance for the embedded portion is then:

$$\lambda_i = C_x \frac{20}{m\, q} \left[\frac{h_2}{b_s} + \frac{h_1}{3\, b_s} + 0.2 + \frac{g}{2\, \tau_s} \right] \tag{39a}$$

The end winding leakage for machines with non-magnetic field coil retaining rings is very similar to that for salient-pole machines, but an additional empirical factor of 1.2 is used for the increased axial divergence. The formula may be further simplified by using average proportions:

$$\lambda_e' = \frac{13\, d}{p\, l} \tag{40a}$$

For machines with magnetic retaining rings, the leakage under steady state conditions is increased by the presence of the ring. Under normal conditions, the greatest effect of saturation is in the tapered section next to the rotor body, and a rough approximation to the resultant field may be had by assuming that the effect is equivalent to cutting out this tapered section.

Numerous two dimensional flux plots constructed on this basis indicate that the increased leakage may be accounted for by adding $\left(\frac{13\,d}{p\,l}\right)$ to the specific permeance. Hence, for machines with magnetic retaining rings, it is necessary to use a different specific permeance for the end winding leakage for steady state conditions:

$$\lambda_e = \lambda_e' + \frac{13\,d}{p\,l} \tag{41a}$$

Under initial sudden short-circuit conditions, this additional leakage path is completely saturated, and the increased leakage will be neglected.

The total leakage reactance for transient and subtransient conditions is:

$$x_l' = X\,[\lambda_i + \lambda_B + \lambda_e'] \tag{42a}$$

For machines with non-magnetic retaining rings, the leakage reactance for steady state conditions is the same as (x_l') given above, but for a machine with magnetic retaining rings:

$$x_l = X\,[\lambda_i + \lambda_B + \lambda_e] \tag{43a}$$

II. Reactances of Armature Reaction (x_{ad} and x_{aq}), and Synchronous Reactances (x_d and x_q)

The flux distribution coefficients may be defined in the same way as for salient-pole machines, but a factor (C_f) is required in place of the average of the field form (C_p). *C_f is the ratio of the interlinkage with the field to that which would be produced with a uniform gap and a concentrated field winding.*

The constants will be calculated assuming the flux to go straight across the air gap. On this basis:

$$C_1 = \frac{8}{\pi^2 K_{rs}}\left(\frac{\sin \gamma \frac{\pi}{2}}{\gamma}\right) + \frac{4}{\pi}\left(\frac{K_{rs}-1}{K_{rs}}\right)\cos \gamma \frac{\pi}{2} \tag{44a}$$

See curves, Fig. 5.

The exact equation for C_m is long, but if the increase in gap due to slotting is neglected, a very good approximation is obtained.

$$C_m = \frac{\pi^2}{8}\left(\frac{\gamma}{\sin \gamma \frac{\pi}{2}}\right) \tag{45a}$$

See curve, Fig. 5. The coefficient C_{d1} is exactly

$$C_{d1} = \left[1 - \frac{K_{rs}-1}{K_{rs}}\left\{\gamma - \frac{\sin \gamma \pi}{\pi}\right\}\right],$$

but it may also be calculated as:

$$C_{d1} = C_m\,C_1 \tag{46a}$$

The quadrature-axis coefficient

$$C_{q1} = \left[1 - \frac{K_{rs}-1}{K_{rs}}\left\{\gamma + \frac{\sin \gamma \pi}{\pi}\right\}\right] \tag{47a}$$

The factor C_f may be calculated as:

$$C_F = \left[(1-\gamma) + \frac{\gamma}{3\,K_{rs}}\right] \tag{48a}$$

The reactances of armature reaction are calculated by the same formulas as for salient-pole machines: **(9a)** and **(10a)** or **(11a and 12a)**; using the coefficients calculated by **(44a)**, **(45a)**, **(46a)**, and **(47a)** given above. The synchronous reactances are given by equations **(13a)** and **(14a)**

III. Field Leakage and Transient Reactance (x_d') Field Leakage Specific Permeance (λ_F)

The rotor slot leakage permeance per cm. is similar to the stator, but expressed as a specific permeance for the field it is:

$$\lambda_{Fs} = \frac{4\,(3.19)\,P}{Q_r}\left[\frac{h_{r2}}{b_r} + \frac{h_{r1}}{3\,b_r} + 0.2 + \frac{g}{2\,\tau_{rs}}\right] \tag{49a}$$

The end leakage was calculated by determining the flux per pole per inch closing about the coil ends. The retaining ring saturation was accounted for by assuming the effect equivalent to cutting out the tapered section of the ring, as discussed for (λ_e). An approximation based on these assumptions and using average proportions was found to be:

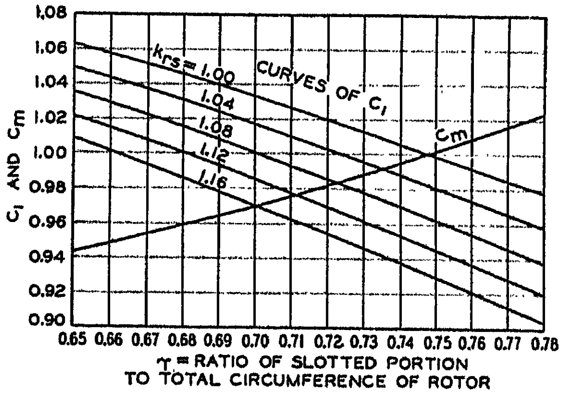


Fig. 5—Flux Distribution Coefficients for Turbine Generators

$$\lambda_{Fe} = \frac{35\,d}{p^2\,l} \tag{50a}$$

The specific permeance for field leakage is:

$$\lambda_F = (\lambda_{Fs} + \lambda_{Fe}) \tag{51a}$$

The unsaturated transient reactance (x_{du}') can be derived in the same manner as for salient-pole machines, except that C_f should be used instead of C_p. However, for any normal distribution of field turns, a simpler solution may be obtained by neglecting the harmonics of the turns distribution of the field. Such harmonics produce entirely negligible mutual interlinkage, and might be treated as additional field leakage, but for normal machines this is also negligible. All the flux across the gap may then be assumed mutual flux, and if the mutual reactance were very high, the fundamental ampere turns of the field would equal that of the armature. The actual field ampere turns would be C_m times the fundamental of the armature, and the fundamental flux across the gap required to produce zero net interlinkage is $\frac{4}{\pi} C_m$ times the actual field leakage. Hence, the true field leakage with respect to the armature, expressed as an armature reactance, is:

$$x_F = X \frac{4}{\pi} C_m^2 \lambda_F \qquad (52a)$$

The effective field leakage is the true field leakage (x_F) added in parallel with the mutual reactance, which on the above assumptions is x_{ad}.

$$x_F' = x_F \left(\frac{x_{ad}}{x_{ad} + x_F} \right) \qquad (53a)$$

The transient reactance is determined as for salient-pole machines, equations (**19a**) and (**20a**).

IV. EFFECTIVE DAMPER LEAKAGE (x_{Dd}') AND (x_{Dq}')

The solid iron and metallic wedges of a turbine generator rotor act as an effective damper winding. The actual penetration of flux into the solid iron depends on the resultant ampere turns acting and the frequency of pulsation. The value of the reactance which is effective in the first instant may be approximated by assuming no decrement and by using the maximum ampere turns per inch to determine an effective depth of penetration. For most turbine generators, the maximum ampere conductors per inch, corresponding to initial symmetrical short-circuit current, is around 16,000.

The direct-axis damper leakage is determined by the depth of flux penetration in the rotor teeth and wedges under sudden short-circuit conditions. The ampere conductors per inch over the center of this section pulsate between zero and twice the value, due to the symmetrical current. The effective permeability at the surface, for these maximum ampere turns, is about 2. Assuming this constant throughout, the formula given by Steinmetz for flux penetration in deep solid parts can be applied. For 60 cycles, the flux penetrates to about 0.6 inch, which is equivalent to a path in air of depth $\delta_d = 1.2$ inches at 60 cycles; (for 25 cycles, rated frequency $\delta_d = 1.8$). The direct-axis leakage may be still further restricted by the slot. The flux across the slot will be assumed to penetrate to the bottom of the wedge. Half of the leakage flux going tangentially in the gap was included in the armature leakage. Expressing these relations as a specific permeance:

$$\lambda_{Dd} = \frac{3.19\ p}{d} [g + \delta_d + h_{r2}] \qquad (54a)$$

The quadrature-axis effective damper leakage depends mainly on the flux penetration in the solid pole center. The magnitude and frequency of the pulsation of ampere turns per inch acting over the pole center vary with conditions of short circuit. For a line-to-line fault, a double frequency pulsation of ampere turns is produced by the symmetrical current and a rated frequency pulsation due to asymmetrical current. The resulting maximum ampere conductors per inch are a little more than half the value used above, but at double frequency the penetration is essentially the same ($\delta_q = 1.2$) for 60 cycles (and $\delta_q = 1.8$ for 25 cycles). For a short circuit from load, where quadrature-axis flux is involved, the resultant ampere conductors per inch are about the same as given above for the direct-axis, and the effective penetration is again δ_q. Expressing these relations as a specific permeance:

$$\lambda_{Dq} = \frac{3.19}{d} [g + 2\,\delta_q] \qquad (55a)$$

The effective damper leakage reactances (x_{Dd}') *and* (x_{Dq}') are calculated as for salient-pole machines, equations (**24a**) and (**28a**).

V. SUBTRANSIENT AND NEGATIVE-SEQUENCE REACTANCES

The subtransient reactances x_d'' and x_q'' may be calculated as for salient-pole machines with dampers (**25a**) and (**29a**). The negative-sequence is determined as the average of x_d'' and x_q'', equation (**31a**). It will be seen that there is very little difference between x_d'' and x_q'', and the tests described in the companion paper[1] show that they do actually become very nearly equal at high currents. For most practical purposes, it should be necessary to calculate and test only x_d''.

VI. ZERO-SEQUENCE REACTANCE

For turbine generators, the zero-sequence belt leakage may be approximated by using the direct-axis damper leakage specific permeance (λ_{Dd}) reduced by the ratio $\frac{k_{xo}}{k_x}$ for chording.

$$\lambda_{Bo} = \frac{k_{xo}}{k_x} \lambda_{Dd} \qquad (56a)$$

The remainder of the formula is the same as for salient-pole machines (**32a** and **34a**):

$$x_o = X\,(\lambda_{io} + \lambda_{Bo} + 0.2\,\lambda_e') \qquad (57a)$$

VII. TIME CONSTANTS T_{do}', T_d', AND T_d

The self inductance of the field in henrys is:

$$L_f = N_p^2\, p\, l\, 10^{-8} \left[C_f \left(3.19 \frac{\tau}{g'} \right) + \lambda_F \right] \qquad (58a)$$

The open-circuit time constant will be calculated, neglecting damping currents in the solid iron, hence is the same as equation (**36a**).

The short-circuit time constant T_d' and armature time constant (T_a) are calculated as for salient-pole machines (**37a**) and (**38a**).

SYMBOLS

NOTE: The symbols for the characteristic reactances and time constants are given in the introduction, Section I. The symbols for the components of reactance are given in Section II. The symbols for the specific permeances and the flux distribution coefficient are given as they are defined and calculated in Appendixes A and B.

For symbols representing machine dimensions, see also Fig. 6.

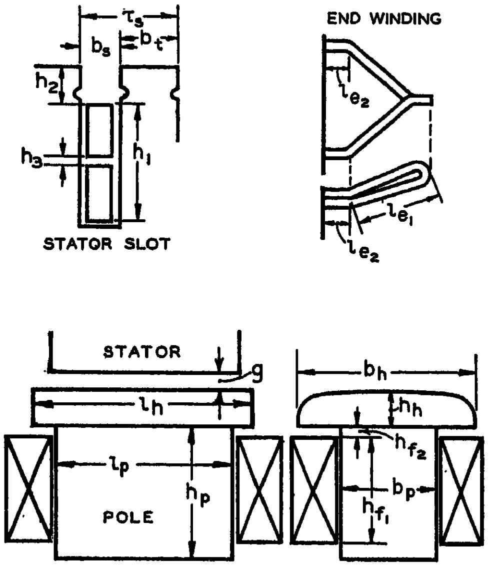


FIG. 6—DETAILS

A = ampere conductors per inch (amperes per slot ÷ slot pitch)
b_{b1} = width of damper bar
b_{b2} = width of slot above damper bar
b_h = width of pole head
b_p = width of pole
b_{rs} = width of rotor slot
b_s = width of stator slot
b_t = width of stator tooth
B_g = air gap density over pole center (at rated voltage)
B_1 = maximum fundamental density at rated voltage
C = number of parallels in the stator winding
d = inside diameter of armature (armature bore)
d_r = rotor diameter
E_{ph} = rated phase voltage (phase winding voltage)
f = rated frequency
F_{st} = ratio of saturated to unsaturated transient reactance (an empirical constant used here as 0.88)
g = actual (single) air gap in pole center
g' = effective air gap, including increase in gap due to stator slots and vents and end fringing
h_{b1} = depth of damper bar
h_{b2} = depth of slot above the damper bar
h_{f1} = depth of field coil
h_{f2} = distance between field coil and pole head
h_{r1} = depth of conductors in the rotor slot
h_{r2} = depth of rotor slot above the conductors
h_1 = depth of conductors in stator slot
h_2 = depth of stator slot above the conductors
h_3 = distance between top and bottom coil sides
I_{ph} = rated phase winding current
k_d = distribution factor for stator winding
k_p = chord factor of the stator winding
k_x = reduction of slot reactance due to chording
k_{xo} = reduction of zero sequence slot reactance due to chording
k_{rs} = Carter's coefficient for rotor slots
l = core length (including vent ducts)
l_b = length of damper bar
l_{e1} = extension of bent section of end winding
l_{e2} = length of straight section of end winding
l_h = length of pole head (including magnetic coil supports)
L_f = total self inductance of the field
m = number of phases
M_A = maximum fundamental armature ampere turns
M_g = air gap ampere turns at no-load and rated voltage
M_m = "demagnetizing ampere turns;" field ampere turns required to balance armature reaction at rated current (zero power factor)
n_b = number of damper bars per pole
n_s = number of conductors per slot
N_p = number of field turns per pole
p = number of poles
P_s = permeance per cm. of slot
q = slots per phase per pole
Q_r = total rotor slots
r_a = d-c. resistance of armature in per cent
R_f = field resistance in ohms at 75 deg. cent.
X = reactance factor, per cent reactance for unit specific permeance. See Section II
y = coil throw (number of slots spanned)
α = "pole embrace" ratio of pole arc to pole pitch
γ = ratio of slotted portion to total circumference of a turbine generator rotor
δ_d = depth of an equivalent path in air for the pulsating flux in the rotor teeth
δ_q = depth of an equivalent path in air for the pulsating flux in a solid pole center
λ = "specific permeance:" effective flux per pole per inch of length for unit ampere turns. See Section II
τ = pole pitch on stator diameter
τ_b = pitch of damper bars
τ_r = pole pitch on rotor diameter
τ_{rs} = rotor slot pitch
τ_s = stator slot pitch

Discussion

M. L. Henderson: Mr. Kilgore's paper is unquestionably an important contribution to the science of synchronous machine design. He has given formulas for the calculation of a larger number of the principal design constants than have heretofore been collected in a single paper. Many of these formulas have been derived on a more fundamental basis than before, while some are more approximate than previous expressions.

The end-winding leakage is accounted for by a method slightly different from that used by Mr. Alger, but comparative results for average machines indicate but little difference in the final results. In fact if the effective end-winding extension $(2\, l_{e2} + l_{e1})$ is assumed equal to the peripheral span of the coil Mr. Kilgore's formula gives almost exactly the same end-winding leakage reactance as does Mr. Alger's expression. The expression (**3a**) for the end-winding leakage permeance, as printed, should evidently be divided by the core length, l. Formula (**40a**) for the end-winding leakage permeance of turbine generators results from (**3a**) provided that the effective end winding extension, including both ends, is taken as 86 per cent of the pole pitch. Considering the range of pitch and the relative importance of end-winding reactance in turbine generators, it seems better to retain the actual dimensions in this formula. For an actual two-pole machine on which these formulas were tried out, (**40a**) gave an end-winding leakage permeance of 6.3, while the expression derived from (**3a**) gave a value of 4.7, including the empirical factor of 1.2.

Mr. Kilgore states that his air-gap flux distribution coefficients, C_1, C_{d1} and C_m can be calculated for salient-pole machines from curves given in Mr. Wieseman's paper on *Graphical Determination of Magnetic Fields*, TRANS. A. I. E. E., Vol. 46, p. 141, but does not give the relation of his coefficients to those given by Mr. Wieseman. The relations are as follows:

by Kilgore		by Wieseman
C_1	=	A_1
C_{d1}	=	A_{d1}
C_{q1}	=	A_{q1}
C_p	=	$\dfrac{2\, A_1\, K_\phi}{\pi}$
C_m	=	K_a, as defined by Mr. Alger

Some unpublished work of Prof. A. A. Bennett, since the publication of Mr. Wieseman's paper, has shown that in agreement with Mr. Kilgore, K_a (or C_m) is dependent only upon the ratio of pole arc to pole pitch, but he obtains values 1 to 2 per cent higher than Mr. Kilgore's. However, we believe, from Prof. Bennett's work, that the quadrature coefficient, C_{q1}, depends upon the ratios of maximum to minimum gap and minimum gap to pole pitch as well as upon the ratio of pole arc to pole pitch. For example C_{q1} for a 70 per cent pole arc varies from 0.43 to 0.55 with reasonable variations in the other ratios, while Mr. Kilgore's curve gives 0.50.

From the standpoint of those who attempt to use and compare the various formulas for synchronous machine constants it is to be hoped that the nomenclature for machine dimensions, number of phases, number of slots, etc., will soon reach something like a steady state. Regardless of the merits of the individual systems, a great deal of the user's time would be saved if it were not necessary to literally translate one set of formulas into another nomenclature to compare them with the results of another writer.

P. L. Alger: The most novel elements of Mr. Kilgore's paper are the inclusion of the tooth tip leakage fringing as an additional term in the slot reactance (equation (**1a**)), the use of flux distribution coefficients independent of the rounding of the pole (Fig. 4), and the formulas for the damper winding leakage. All of these proposals seem to be in the right direction, and fundamentally desirable, although in each case approximations are involved which may be important in some cases.

The calculation of saturated reactance is not considered, however, the simple proposal being made that an empirical factor of 0.88 be applied to unsaturated values to determine the saturated values. I believe that it is only feasible at the present time to determine the unsaturated reactances in routine design work, whether by test or by calculation, and that it is desirable to establish saturation factors such as that proposed. However, the effect of saturation must certainly vary, depending on the type of machine and on the magnitude of the short-circuit current, so that no single factor adequately represents the facts. The effects of saturation are difficult to calculate, and a large body of test data should be obtained before any method of calculating saturation effects can be established. A complete theory must reconcile the different values of saturated reactance obtained by short circuit and static tests, and must also explain the variations in time constant with saturation.

I believe that, roughly speaking, the saturation factor decreases uniformly as the ratio of the short-circuit current to the full load current increases, and that this saturation factor is of the same order of magnitude for all types of machine for a given value of per unit short-circuit current. This effect can be roughly represented by taking the saturated value of the transient reactance as a definite fixed amount, say 0.05 in per unit value, less than the unsaturated reactance value. Thus, a machine having an unsaturated transient reactance of 40 per cent might have a saturated value of 35 per cent, while one having an unsaturated reactance of 15 per cent might have a saturated reactance of 10 per cent.

I think that as a temporary measure some such basis as this should be agreed upon for the determination of the saturated reactance values, rather than taking any arbitrary constant ratio for all cases, and I certainly believe that the factor of 0.88 proposed by Mr. Kilgore, is too high for the cases of low reactance machines such as turbine alternators.

Transient Oscillations in Distributed Circuits
With Special Reference to Transformer Windings

BY L. V. BEWLEY*
Associate, A. I. E. E.

Synopsis.*—This paper is essentially a mathematical study of transient voltages in transformer and other distributed windings, and is primarily concerned with showing the effects of wave shape, circuit constants and neutral impedances on the voltage distributions, and how these distributions may be controlled or changed. In the appendix there is derived the general differential equation for a circuit consisting of distributed self and mutual inductance, series and shunt capacitance, series resistance, and conductance along the stack and to ground. This equation is solved for the following conditions: (1) initial and final conditions with generalized impedance in the neutral; (2) grounded neutral; (3) isolated neutral for zero losses; and (4) capacitance in the neutral when the losses and mutual inductance are neglected. Equations are given corresponding to a number of different applied waves, showing the effects of wavelength, wave front, damped and sustained oscillations, and typical lightning waves, and these effects are illustrated by curves and oscillograms. Equations are also given for the potential difference between any two points on the winding and for the voltage gradients. Tables are included showing the influence of the various circuit constants on the amplitude and frequency of oscillation, linear velocity and surge impedance of harmonic waves, and the type of propagation. These effects are illustrated by curves of the potential distribution at different instants of time. Methods of controlling the transient so as to prevent or alleviate abnormal voltage distributions are discussed at length. An equivalent circuit is developed which serves as an approximation for a transformer as far as external reactions are concerned.*

* * * * *

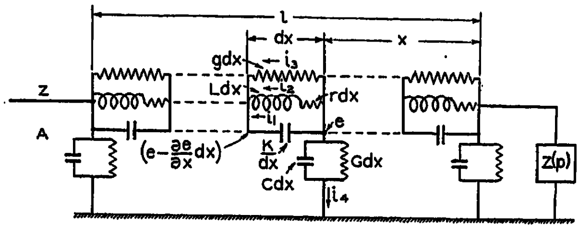
I. INTRODUCTION

THE purpose of this paper is to continue the study of oscillations in transformers and particularly to derive complete mathematical equations for the transient oscillations which occur in transformer windings and other distributed circuits when subjected to incident waves of arbitrary shape. The effects of the losses, neutral impedances, circuit parameters, and shields are discussed in detail, and the appropriate equations derived. While the analysis is necessarily based on ideal circuits and subject to the restrictions of certain simplifying assumptions; nevertheless the theoretical considerations not only describe the general characteristics of the transient, but give closer quantitative agreement with tests than might be expected. The principal discrepancies are due to the assumptions (made in the interests of mathematical simplicity) concerning the series capacitance paths and the mutual inductance. In order to avoid a complicated partial differential equation with variable coefficients it was necessary to adhere to the assumptions of a linearly graded mutual inductance.[3] Moreover, it was expedient to ignore all circuit discontinuities, such as the lumping of the winding into pancake coils, breaks for taps, interleaving, etc. These circuit discontinuities give rise to localized oscillations which are superimposed on the principal oscillations, and while these do not add materially to the maximum potentials to ground, yet they may greatly increase the turn-to-turn stresses.

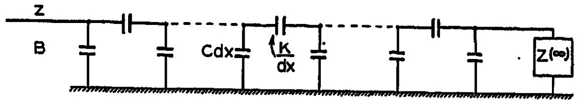
The author's indebtedness to the papers in the bibliography, which he has consulted very freely, will be obvious to the informed reader on this subject.

II. THE GENERAL CIRCUIT

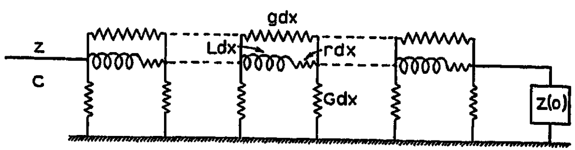
The Circuit Constants. The transient in a distributed winding, such as that of a transformer, is characterized by a complicated network of circuit constants. These include the self and mutual inductances; the capacitances from turn to turn, to tank, to the core and between coils; the dielectric loss constants, and the series resistance of the winding as modified by skin effect.



COMPLETE EQUIVALENT CIRCUIT



CIRCUIT CONTROLLING INITIAL DISTRIBUTION



CIRCUIT CONTROLLING FINAL DISTRIBUTION

FIG. 1—IDEAL COMPLETE CIRCUIT OF A TRANSFORMER

For purposes of analysis the circuit may be simplified to that shown in Fig. 1A. The capacitances from the winding to the core and to the tank have been combined as a single capacitance C per unit length to ground. The coil-to-coil capacitance along the stack is K per unit length. The total flux linkages at any point of the winding consists of those due to the mutual flux of the entire winding, and the partial interlinkages of the leakage flux. The effective inductance L, which includes these partial interlinkages is not, therefore, a pure self-inductance. It is defined, on the assumption of a linearly graded mutual flux, in Appendix I.

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*Power Trans. Engg. Dept., General Electric Co., Pittsfield, Mass.

[3] For references see Bibliography.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

Since the transient is of high frequency, the skin effect in the conductors probably represents the principal copper loss. This transient skin effect is too complicated to express analytically, but since it is known that the losses do not have much influence on the first cycle of the fundamental oscillation, it is sufficient to represent the copper losses by a series resistance r. There remain the dielectric losses caused by the difference of potential between winding and ground, and from point to point along the stack. These are accounted for by the conductances G and g respectively. In practise, the neutral of a transformer may be directly grounded, isolated, or connected to ground through some sort of impedance, such as a resistance, reactor, or impedor. This grounding impedance is represented in Fig. 1 as $Z(p)$ where the $p = \partial/\partial t$ implies that the impedance can be any general combination of resistances, inductances, capacitances, etc. The other terminal of the winding is connected to the incoming transmission line or cable of surge impedance z.

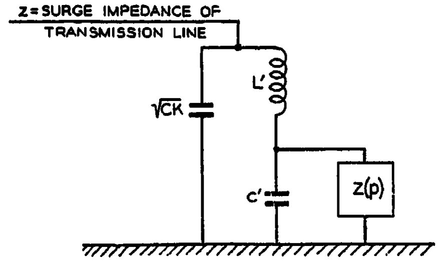

Fig. 2—Equivalent Circuit of Transformer to Traveling Waves

Equivalent Circuit for Terminal Reactions. In Appendix I it is shown that at the first instant the transformer behaves as a capacitance circuit, Fig. 1B, having an effective capacitance with respect to the terminal of

$$\sqrt{C K}$$

Eventually, however, the transformer acts as a pure inductance L', so that there is a transition period during which, by equation (63) of Appendix I, the neutral voltage of an isolated neutral transformer oscillates with a fundamental frequency[3]

$$f = \frac{\pi}{4 \sqrt{L (4 C + \pi^2 K)}}$$

and rises to practically double the terminal voltage. If the neutral is grounded, there are, of course, no oscillations at the neutral. These considerations suggest the circuit shown in Fig. 2 as the approximate terminal equivalent circuit of a transformer, where the capacitance C' is chosen so that for an isolated neutral the neutral voltage has a period of oscillation equal to f above. That is

$$f = \frac{1}{2 \pi \sqrt{L' C'}} = \frac{\pi}{4 \sqrt{L (4 C + \pi^2 K)}}$$

$$\therefore C' = \frac{4 L (4 C + \pi^2 K)}{L' \pi^4}$$

where L is the effective inductance defined following equation (8) in Appendix I, and L' is the short-circuited inductance of the transformer. It will be observed that the circuit satisfies the following conditions:

1. At the first instant the circuit behaves as a capacitance $\sqrt{C K}$ to ground.
2. For a grounded neutral the neutral voltage is zero.
3. For an isolated neutral the neutral voltage oscillates at the fundamental natural frequency of the transformer, and approaches an upper limit of double the terminal voltage.
4. Resistance in the neutral decreases the period of oscillation and limits the rise of the neutral voltage to a value less than twice the terminal voltage.
5. The circuit finally behaves as an inductance L'.

This circuit has been verified by tests results, and is instrumental in tremendous simplifications in the analysis of transformer oscillations. While the introduction of such approximations is never justifiable from a mathematical point of view, yet they are appropriate for engineering purposes. Still further simplifications can usually be made. The surge impedances of the harmonic waves comprising the internal oscillations in the windings are many times the surge impedance of the transmission line, and because of this great disparity in value these harmonic waves are reflected from the line terminal practically as from a grounded end. Conversely, the incident wave on the transmission line is practically completely reflected, so that the terminal voltage is very nearly twice the traveling wave voltage. For this reason the surge impedance of the transmission line does not come into the picture, except for very long waves; and it is often sufficient to compute the internal oscillations of the transformer on the assumption that twice the incident wave is directly applied to the terminals. When greater accuracy is required the equivalent circuit of Fig. 2 can be used to determine the terminal voltage, and then this voltage used as the impressed voltage for calculating the internal oscillations. Ordinarily the capacitance $\sqrt{C K}$ may be ignored, unless there is an inductance in series with the transformer.

The Initial Distribution. When a wave with an abrupt front reaches the terminal of a transformer, the rate of change of potential in that first instant is infinite, and therefore the currents flowing through the capacitance paths of the winding are also infinite. But the current in the inductance is zero, and the currents in the resistance elements are all finite. Therefore the initial distribution depends only on the capacitance elements of the circuit, Fig. 1B, and the nature of the neutral impedance. In Appendix I it is shown that the distribution is of the form

$$e = \frac{A \cosh \alpha x + \sinh \alpha x}{A \cosh \alpha + \sinh \alpha}$$

where

$\alpha = \sqrt{C/K}$
$A = [p\, Z(p) \sqrt{C K}]$ as $p \rightarrow \infty$
$Z(p)$ = neutral impedance
K = series capacitance
C = shunt capacitance
x = fraction of winding from neutral end.

In a normal transformer α is of the order of 5 to 30. In a non-resonating transformer it is nearly zero.

A few representative combinations for A are given in the following table:

Neutral impedance.................	$Z(p)$	A
Directly grounded..................	0	0
Isolated neutral....................	∞	∞
Resistance.........................	R_o	∞
Inductance.........................	$p\, L_o$	∞
Capacitance.......................	$1/(p\, C_o)$	$\sqrt{C K/C_o}$
Inductance and capacitance in series.	$p\, L_o + 1/p\, C_o$	∞
Inductance and capacitance in parallel	$p\, L_o/(1 + p^2 L_o C_o)$	$\sqrt{C K/C_o}$
Resistance and capacitance in parallel	$R_o/1 + p\, R_o C_o)$	$\sqrt{C K/C_o}$
Resistance and inductance in parallel.	$R_o L_o p/(R_o + p\, L_o)$	∞

In all cases for which $A = \infty$ the initial distribution is given by

$$e = \frac{\cosh \alpha x}{\cosh \alpha}$$

It is evident that only an uninterrupted capacitance from the neutral to ground, or a directly grounded neutral can change the initial distribution from that corresponding to an isolated neutral.

In Fig. 3 is a set of curves showing the initial distribution corresponding to a perpendicular wave front.[3] Notice that for values of α in the neighborhood of $\alpha = 10$ the initial distribution is practically independent of the neutral impedance (as characterized by A). These curves also clearly show that the distribution becomes more nearly linear as α decreases, that is, as the ratio $\sqrt{C/K}$ decreases. In other words, the distortion in the initial distribution is caused by the capacitance to ground C, and can be improved either by decreasing C or by increasing the series capacitance K. This possibility is of primary importance in connection with electrostatic shielding, and is fully discussed in Part V of this paper.

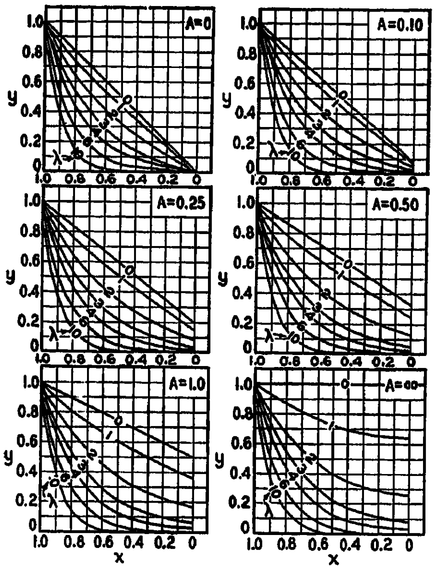

FIG. 3—INITIAL AND FINAL DISTRIBUTION FACTOR

$$\frac{e}{E} = \frac{A \cosh \lambda x + \sinh \lambda x}{A \cosh \lambda + \sinh \lambda}$$

$\lambda = \alpha$ for initial distribution
$\lambda = \beta$ for final distribution

The Final Distribution. After the transient oscillations caused by the application of an infinite rectangular wave at the line terminal have died out (theoretically at $t = \infty$), there remains a residual distribution. The capacitance elements then act as open circuits and the inductance elements as short circuits, and the distribution is entirely determined by the resistance elements, Fig. 1C. The damping out of the oscillations is due not only to the internal losses (skin effect, dielectric and iron losses), but also to the junction losses at the terminals where energy is lost by the refraction of waves to the line and to the neutral impedance. In Appendix I it is shown that the final distribution is given by an equation having exactly the same form as for the initial distribution, but whose constants are, of course, different. It is

$$e = \frac{A \cosh \beta x + \sinh \beta x}{A \cosh \beta + \sinh \beta}$$

where

$$\beta = \sqrt{\frac{r\, G}{1 + g\, r}}$$

$$A = Z(o) \sqrt{\frac{G}{r}(1 + g\, r)}$$

r = series resistance
g = conductance along winding
G = conductance to ground
$Z(0) = Z(p)$ when $p = 0$

In all cases for which $Z(o) = 0$, and this includes all combinations in which there is a pure inductance between the neutral and ground, the distribution is

$$e = \frac{\sinh \beta x}{\sinh \beta}$$

In all cases for which $Z(0) = \infty$, and this includes a capacitance in series as part of the neutral impedance, the distribution is

$$e = \frac{\cosh \beta x}{\cosh \beta}$$

The distributions are given for a range in the values of β and A in Fig. 3. In an actual transformer, the value of β is so small that

$$\cosh \beta x \cong 1$$
$$\sinh \beta x \cong \beta x$$

and the distribution is the straight line

$$e = \frac{(1 + g r)\, Z(0) + r x}{(1 + g r)\, Z(0) + r}$$

Theoretically, by the use of auxiliary resistances having a decided negative characteristic it may be desirable to control the final distribution—or what is the same thing, the axis of oscillations—during the transient. Such control could be used both to reduce the amplitude of the oscillations and accelerate their decay, or to prevent the rise of the neutral voltage.

The Transient. The general differential equation of the complete circuit of Fig. 1 is derived in Appendix I, and solutions obtained for a grounded and an isolated neutral. The solutions have the form

e = (final distribution) + (harmonic standing waves).

The amplitudes of the space harmonics are given by the Fourier analysis of the initial distribution with respect to the final distribution, and are therefore smaller, the more nearly these two distributions are alike. The two solutions, when the losses are neglected, are discussed in detail under Parts III and IV of this paper. The solution, including the losses, for the grounded neutral case, is of the form

$$e = E\,\frac{\sinh \beta x}{\sinh \beta} + E \sum_{1}^{\infty} \frac{2\,(-1)^s\, s\pi\,(\alpha^2 - \beta^2)}{(\beta^2 + s^2\pi^2)\;(\alpha^2 + s^2\pi^2)}\, \epsilon^{-\gamma_s t} \cos \omega_s t \sin s\pi x \tag{45}$$

where

$$\alpha = \sqrt{\frac{C}{K}} \text{ and } \beta = \sqrt{\frac{r G}{1 + g r}}$$

If $r = g = G = 0$, then $\beta = 0$ and $\gamma_s = 0$ and the solution reduces to that given in Part III. The effect of the losses is four-fold:

1. Oscillations are damped out by exponential decrement factors.
2. Decreased amplitudes of oscillations.
3. Decreased frequencies of oscillation.
4. Non-linear final distribution.

It is evident that all oscillations vanish if $\alpha = \beta$. But this is the condition that the initial and final distributions are alike. Therefore the criterion for no oscillations is that the initial and final distribution shall be the same, and it is immaterial whether the adjustment be made on either distribution, or on both.

A general solution for any impedance $Z(p)$ in the neutral is impossible, nor can explicit solutions be obtained for the most simple specific cases, but must depend upon finding the roots of transcendental equations. For this reason pure mathematical analysis ceases to be profitable. However, good approximate results may be obtained by using the equivalent circuit of Fig. 2 and applying the principle of superposition. This method is discussed in detail in Part V.

III. Grounded Neutral

In this section there are considered the circuits shown in Fig. 4. The wavy line coil indicates that the flux is due to pure self-inductance, whereas the looped coil indicates that mutual inductance is also present between points along the winding. In the interests of simplicity the losses are neglected. Solutions are obtained for the different wave shapes shown in Fig. 6, and the effect of wavelength, wave front, and frequency of applied voltage are evaluated.

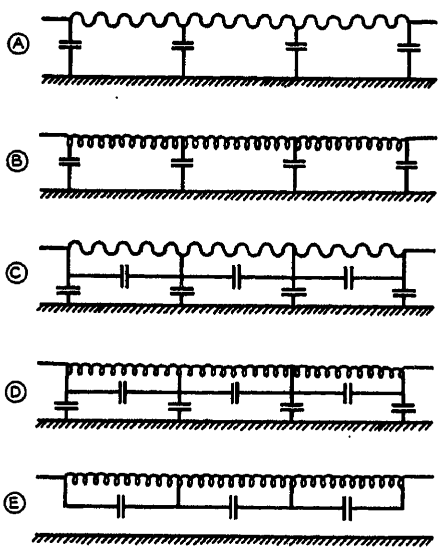

Fig. 4—Circuits Used in Calculations

The potential e at point x of any of these five circuits, measuring from the grounded terminal, can be expressed, as shown in Appendix I, by the identical equations (for an infinite rectangular applied wave)

$$e = xE + E \sum_{1}^{\infty} A_s \sin s\pi x \cos \omega_s t \tag{1a}$$

$$= xE + E \sum_{1}^{\infty} \frac{A_s}{2} [\sin (s\pi x + \omega_s t) + \sin (s\pi x - \omega_s t)] \tag{1b}$$

$$= E \sum_{1}^{\infty} \left[A_s \cos (s\pi - \omega_s t) - \frac{2}{s\pi}\right] \cos s\pi \,.\, \sin s\pi x \tag{1c}$$

These three equations represent the same phenomenon from three different points of view:

Equation	Point of view
1 a.....	(Fixed distribution) + (harmonic standing waves)
1 b.....	(Fixed distribution) + (pairs of harmonic traveling waves)
1 c.....	Simple traveling waves in the case of circuit Fig. 4A

The amplitude A_s, angular velocity ω_s, linear velocity v_s, surge impedance z_s, initial and final distributions, and type of propagation for each of the four circuits under consideration are given in the following table.

Circuit	(L, C)	(M, C)	(L, C, K)	(M, C, K)
A_s	$\frac{2\cos s\pi}{s\pi}$	$\frac{2\cos s\pi}{s\pi}$	$\frac{2\alpha^2\cos s\pi}{s\pi(s^2\pi^2+\alpha^2)}$	$\frac{2\alpha^2\cos s\pi}{s\pi(s^2\pi^2+\alpha^2)}$
ω_s	$\frac{s\pi}{\sqrt{LC}}$	$\frac{s^2\pi^2}{\sqrt{MC}}$	$\frac{s\pi}{\sqrt{L(Ks^2\pi^2+C)}}$	$\frac{s^2\pi^2}{\sqrt{M(Ks^2\pi^2+C)}}$
v_s	$\frac{1}{\sqrt{LC}}$	$\frac{s\pi}{\sqrt{MC}}$	$\frac{1}{\sqrt{L(Ks^2\pi^2+C)}}$	$\frac{s\pi}{\sqrt{M(Ks^2\pi^2+C)}}$
z_s	$\sqrt{\frac{L}{C}}$	$\frac{1}{s\pi}\sqrt{\frac{M}{C}}$	$\sqrt{\frac{L}{C}}\sqrt{\frac{s^2\pi^2}{\alpha^2}+1}$	$\sqrt{\frac{M}{C}}\sqrt{\frac{1}{\alpha^2}+\frac{1}{s^2\pi^2}}$
e $t=0$	0	0	$\frac{\sinh\alpha x}{\sinh\alpha}$	$\frac{\sinh\alpha x}{\sinh\alpha}$
e $t=\infty$	x	x	x	x
Type of propagation	As a rigid distribution	High harmonics ahead	High harmonics behind	High harmonics ahead

These conditions are illustrated in Fig. 5 for the first four circuits of Fig. 4, when $L = M = 5$, $C = 10^{-9}$, and $K = 10^{-11}$.

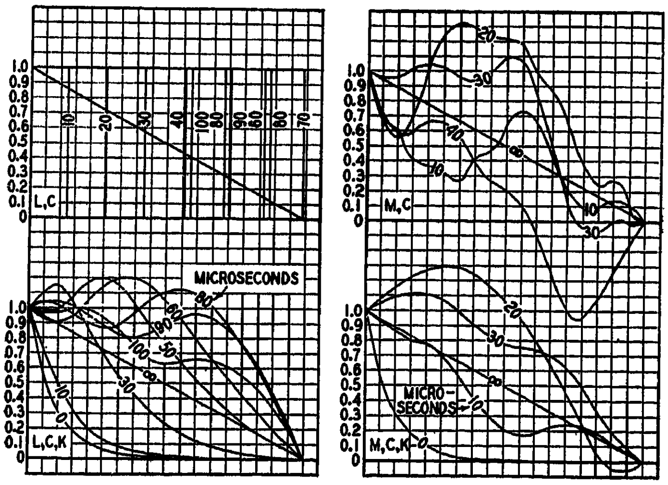

Fig. 5—Internal Distributions

Incident Waves of Arbitrary Shape. The foregoing equations and curves describe the response of the grounded-neutral circuits in Fig. 4 to an infinite rectangular applied wave. If the solution for this case be called $\varphi(t)$ and if the solution corresponding to any applied wave $E(t)$ is required it can be found by means of Duhamel's theorem as

$$e = E(t)\,\varphi(0) + \int_0^t E(\tau)\,\frac{\partial}{\partial t}\cdot\varphi(t-\tau)\,d\tau \tag{2}$$

where, from equation (1),

$$\varphi(t) = x + \sum_1^\infty A_s \sin s\pi x \cos\omega_s t \tag{3}$$

Finite Rectangular Wave. Applying (2) to the finite rectangular wave of length L, Fig. 6B, there is

$$\left.\begin{aligned} e_{(t<L)} &= xE + E\sum_1^\infty A_s \sin s\pi x\cos\omega_s t \\ e_{(t>L)} &= E\sum_1^\infty A_s \sin s\pi x\left[\cos\omega_s t - \cos\omega_s(t-L)\right] \\ &= -E\sum_1^\infty A_s \sin s\pi x\left(2\sin\frac{\omega_s L}{2}\right)\sin\omega_s\left(t-\frac{L}{2}\right) \end{aligned}\right\} \tag{4}$$

Thus the solution is the same as for the infinite rectangular wave up until the time $t = L$. But for $t > L$ the axis of oscillations has shifted from the xE line to the zero axis, and the amplitudes of the harmonics are multiplied by the reduction factor

$$2\sin\frac{\omega_s L}{2} \tag{5}$$

Any particular harmonic is then a maximum for

$$\frac{\omega_s L}{2} = (2n-1)\frac{\pi}{2}$$

where n is an integer. Therefore the wavelength L necessary to make any harmonic s a maximum is

$$L=\frac{(2n-1)\pi}{\omega_s}=\frac{(2n-1)\pi}{2\,\pi\,f_s}=\frac{2\,n-1}{2\,f_s}=(2n-1)\,\frac{T_s}{2} \qquad (6)$$

Thus the wavelength must be an odd multiple of the natural half period of oscillation $T_s/2$. In this case the amplitude of oscillation for that particular harmonic is twice as great for $t > L$ as for $t < L$, but since the axis of oscillations has shifted to the zero axis the voltage to ground does not necessarily increase at any point along the winding. Considering any harmonic alone there is for $t < L$

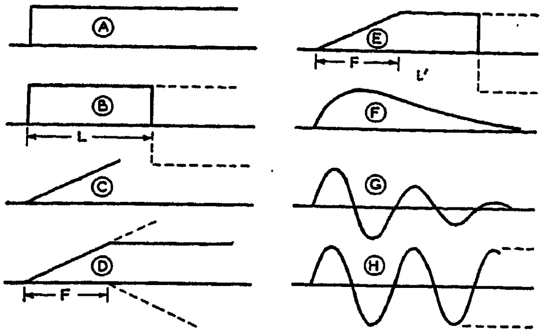

Fig. 6—Wave Shapes Used in Calculations

$$e' = E\,(x + A_s \sin s\,\pi\,x \cos \omega_s\,t) \qquad (7)$$

and this is a maximum when $\cos \omega_s\,t = \cos s\,\pi$ and for

$$\frac{\partial e'}{\partial x} = 0 = E\,(1 + A_s\,s\,\pi \cos s\,\pi\,x) \qquad (8)$$

$$\therefore x = \frac{1}{s\,\pi}\cos^{-1}\frac{(-1)}{s\,\pi\,A_s} \qquad (9)$$

$$e'_{max} = E\left[\frac{1}{s\,\pi}\cos^{-1}\frac{(-1)}{s\,\pi\,A_s} + A_s\sqrt{1-\left(\frac{1}{s\,\pi\,A_s}\right)^2}\right]$$

$$= \frac{E}{s\,\pi}\left[\cos^{-1}\frac{(-1)}{s\,\pi\,A_s} + \sqrt{s^2\,\pi^2\,A_s^2 - 1}\right] \qquad (10)$$

In a grounded-neutral winding A_s is greatest for the fundamental, but cannot exceed $2/\pi$, so that the maximum to which fundamental can raise the voltage is

$$e'_{max}=\frac{E}{\pi}\left[\cos^{-1}\frac{(-1)}{2}+\sqrt{3}\right]=1.218\,E \text{ for } t<L \qquad (11)$$

as compared with

$$e''_{max} = 2\,A_s\,E = \frac{4}{\pi}\,E = 1.272\,E \text{ for } t > L \qquad (12)$$

These relative values are, of course, altered by the contributions of the other harmonics, and A_s is actually always less than $2/\pi$.

Effect of a Linear Front. The solution for the infinite linear wave, Fig. 6c,

$$E\,(t) = a\,t \qquad (13)$$

by Duhamel's theorem is

$$e = a\,t\,x + \sum_{1}^{\infty}\frac{a}{\omega_s}\,A_s \sin s\,\pi\,x \sin \omega_s\,t \qquad (14)$$

Herefrom, the solution for a wave with a linear front of length F and an infinite rectangular tail is found by superimposing two such solutions of opposite sign and displaced by an amount $t = F$, Fig. 6D. It is

$$\left.\begin{aligned} e_{t<F} &= x\frac{E}{F}\,t + E\sum_{1}^{\infty} A_s \frac{1}{F\,\omega_s}\sin s\,\pi\,x \sin \omega_s\,t \\ e_{t>F} &= x\,E - E\sum_{1}^{\infty} A_s \\ &\left[\frac{2}{F\,\omega_s}\sin\frac{F\,\omega_s}{2}\right]\sin\,\omega_s\left(t-\frac{F}{2}\right)\cos s\,\pi\,x \end{aligned}\right\} \qquad (15)$$

For $t > F$ the amplitude of any harmonic is proportional to

$$y_s = \frac{2}{F\,\omega_s}\sin\frac{F\,\omega_s}{2} \qquad (16)$$

This reduction factor is plotted in Fig. 8. It has a maximum of unity occuring at $F = 0$, and then rapidly decreases in magnitude similar to a damped oscillation.

$$y_s = 0 \text{ for } \frac{F\,\omega_s}{2} = n\,\pi \quad \text{or} \quad F = \frac{2\,n\,\pi}{\omega_s} = \frac{n}{f_s} \qquad (17)$$

Thus if the wave front is a multiple of the natural period of oscillation of a particular harmonic, then that harmonic vanishes. If the front is sufficiently long so that the fundamental vanishes, then the harmonics also become negligible.

When a wave of this nature is chopped on the tail, Fig. 6E, the subsequent voltage distribution is found by superimposing an infinite rectangular wave of opposite sign, and displaced back from the origin by an amount L'. The solution then is

$$e_{t>L'} = -\,E\sum_{1}^{\infty} A_s\left[\cos\,\omega_s\,(t-L') - \frac{2}{\omega_s\,F}\sin\frac{\omega_s\,F}{2}\cos\,\omega_s\left(t-\frac{F}{2}\right)\right]\sin s\,\pi\,x \qquad (18)$$

Thus if a wave having a front so slow that it causes no perceptible oscillations, is chopped at a voltage E on the tail, the subsequent distribution will consist of the oscillations corresponding to an infinite rectangular wave of $(-\,E)$ potential, but these oscillations will take place about the zero axis instead of the $(-\,x\,E)$ axis.

Typical Lightning Wave. The characteristic shape of a natural lightning wave—disregarding the minor irregularities—is shown in Fig. 6F, and is represented by

$$E\,(t) = E\,(\epsilon^{-at} - \epsilon^{-bt}) \qquad (19)$$

Then by Duhamel's Theorem there is

$$e = E\,(\epsilon^{-at} - \epsilon^{-bt})\,x + E\sum_{1}^{\infty} A_s \sin s\,\pi\,x \left[\frac{a^2\,\epsilon^{-at}}{a^2+\omega_s^2} - \frac{b^2\,\epsilon^{-bt}}{b^2+\omega_s^2} + \frac{\omega_s}{\sqrt{a^2+\omega_s^2}}\cos\left(\omega_s\,t + \tan^{-1}\frac{a}{\omega_s}\right) - \frac{\omega_s}{\sqrt{b^2+\omega_s^2}}\cos\left(\omega_s\,t + \tan^{-1}\frac{b}{\omega_s}\right)\right] \quad (20)$$

A wave with an infinite tail is obtained by making $a = 0$. Then the above equation reduces to

$$e_{a\,=\,0} = E(1-\epsilon^{-bt})\,x + E\sum_{1}^{\infty} A_s \sin s\,\pi\,x \left[-\frac{b^2\,\epsilon^{-bt}}{b^2+\omega_s^2} + \frac{b}{\sqrt{b^2+\omega_s^2}}\cos\left(\omega_s\,t + \tan^{-1}\frac{\omega_s}{b}\right)\right] \quad (21)$$

Thus the oscillations are partially proportional to the factor b determining the length of the front. When $b = \infty$ the front is perpendicular, and the solution reduces to that of the infinite rectangular wave.

A wave with a perpendicular front and an exponential tail is given by putting $b = \infty$ in (19). Then

$$e = E\,\epsilon^{-at}\,x + E\sum_{1}^{\infty} A_s \sin s\,\pi\,x \left[\frac{a^2\,\epsilon^{-at}}{a^2+\omega_s^2} + \frac{\omega_s}{\sqrt{a^2+\omega_s^2}}\cos\left(\omega_s\,t + \tan^{-1}\frac{a}{\omega_s}\right)\right] \quad (22)$$

Here again, by putting $a = 0$ the solution reduces to that for an infinite rectangular wave.

Damped Oscillations. The importance of this case justifies a separate paper.[9]

Potential Difference Between Points. The potential difference between any two points x_1 and x_2 of the winding, for an infinite rectangular wave is

$$e_1 - e_2 = (x_1 - x_2)\,E + E\sum_{1}^{\infty} A_s\,(\sin s\,\pi\,x_1 - \sin s\,\pi\,x_2)\cos\omega_s\,t$$

$$= (x_1 - x_2)\,E + E\sum_{1}^{\infty} A_s\,2\sin\frac{s\,\pi}{2}(x_1 - x_2)\cos\frac{s\,\pi}{2}(x_1 + x_2)\cos\omega_s t \quad (23)$$

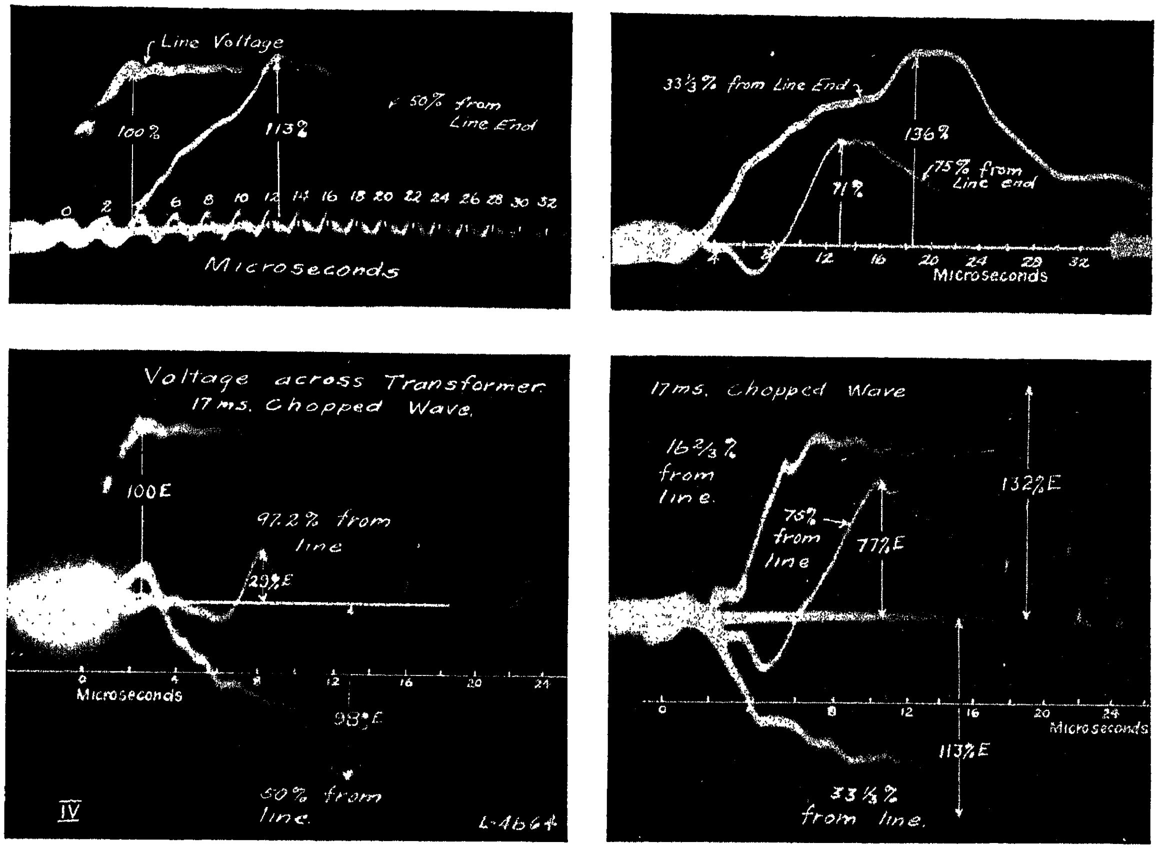

FIG. 7—EFFECT OF CHOPPING WAVE ON THE TAIL

Top, very long applied wave
Bottom, wave chopped at 17 microseconds

Consequently the harmonic voltage between any two points vanishes if

$$\left.\begin{aligned} s\,(x_1 + x_2) &= (2\,n - 1) = \text{an odd integer} \\ s\,(x_1 - x_2) &= 2\,m \qquad\; = \text{an even integer} \end{aligned}\right\} \tag{24}$$

For example, if $x_1 = 2/3$ and $x_2 = 1/3$, then all odd harmonics and all even harmonics which are multiples of six, vanish. Thus the only harmonic voltages between these two points are the 2nd, 4th, 8th, 10th, 14th, etc. The harmonic voltages which can exist between two points of the winding, as fraction of full value, are best pictured by charts. For instance, at $x_1 = 3/4$ and $x_2 = 1/4$ the 1st, 3rd, 5th, etc., cancel out; the 4th, 8th, 12th, etc., are zero; and the 2nd, 6th, 10th, etc., have doubled differences. More generally, for points equal distances from the ends $x_2 = (1 - x_1)$ and

$$\left.\begin{aligned} s\,(x_1 + x_2) &= s = 2\,n - 1 \\ s\,(x_1 - x_2) &= s\,(2\,x_1 - 1) = 2\,m \end{aligned}\right\} \tag{25}$$

Thus there are no odd harmonics in the potential difference between points equidistant from the ends.

Gradients. The gradient, or stress along the stack per unit length of winding, is simply the space derivative $(\partial\, e/\partial\, x)$ of the corresponding voltage equation. Therefore, since x does not appear in the foregoing equations except as (x) or in $(\sin s\,\pi\,x)$, the gradients are given by replacing in the above equations

$$\left.\begin{aligned} x &\text{ with } 1 \\ \sin s\,\pi\,x &\text{ with } s\,\pi \cos s\,\pi\,x \end{aligned}\right\} \tag{26}$$

IV. ISOLATED NEUTRAL

When the neutrals of the circuits shown in Fig. 4 are isolated, and the applied wave is infinite rectangular, the solution is

$$e = E - E \sum_1^\infty B_s \,.\, \cos \frac{s\,\pi\,x}{2} \,.\, \cos \Omega_s\, t \tag{1a}$$

$$= E - E \sum_1^\infty \frac{B_s}{2} \left[\cos\left(\frac{s\,\pi\,x}{2} - \Omega_s\, t \right) + \cos\left(\frac{s\,\pi\,x}{2} + \Omega_s\, t \right) \right] \tag{1b}$$

$$= -\,E \sum_1^\infty \left[B_s \sin\left(\frac{s\,\pi}{2} - \Omega_s\, t \right) - \frac{4}{s\,\pi} \right] \sin \frac{s\,\pi}{2} \cos \frac{s\,\pi\,x}{2} \tag{1c}$$

The amplitude B_s, angular velocity Ω_s, linear velocity V_s, surge impedance Z_s, initial and final distributions, and type of propagation for each of the four circuits of Fig. 4 are given in the following table:

Circuit	(L, C)	(M, C)	(L, C, K)	(M, C, K)
B_s	$\frac{4 \sin s\,\pi/2}{s\,\pi}$	$\frac{4 \sin s\,\pi/2}{s\,\pi}$	$\frac{16\,\alpha^2 \sin s\,\pi/2}{s\,\pi\,(s^2\pi^2 + 4\,\alpha^2)}$	$\frac{16\,\alpha^2 \sin s\,\pi/2}{s\,\pi\,(s^2\pi^2 + 4\,\alpha^2)}$
Ω_s	$\frac{s\,\pi/2}{\sqrt{L\,C}}$	$\frac{s^2\,\pi^2/4}{\sqrt{M\,C}}$	$\frac{s\,\pi/2}{\sqrt{L\,(K\,s^2\,\pi^2/4 + C)}}$	$\frac{s^2\,\pi^2/4}{\sqrt{M\,(K\,s^2\,\pi^2/4 + C)}}$
V_s	$\frac{1}{\sqrt{L\,C}}$	$\frac{s\,\pi/2}{\sqrt{M\,C}}$	$\frac{1}{\sqrt{L\,(K\,s^2\pi^2/4 + C)}}$	$\frac{s\,\pi/2}{\sqrt{M\,(K\,s^2\pi^2/4 + C)}}$
Z_s	$\sqrt{\frac{L}{C}}$	$\frac{2}{s\,\pi}\sqrt{\frac{M}{C}}$	$\sqrt{\frac{L}{C}\left(\frac{s^2\pi^2}{4\,\alpha^2} + 1\right)}$	$\sqrt{\frac{M}{C}\left(\frac{1}{\alpha^2} + \frac{4}{s^2\pi^2}\right)}$
$\underset{t\,=\,0}{e}$	0	0	$E\,\frac{\cosh \alpha\,x}{\cosh \alpha}$	$E\,\frac{\cosh \alpha\,x}{\cosh \alpha}$
$\underset{t\,=\,\infty}{e}$	E	E	E	E
Type of propagation	As a rigid distribution	High harmonics ahead	High harmonics behind	High harmonics ahead

The behavior of an isolated neutral winding to waves of arbitrary shape can be determined by an application of Duhamel's Theorem, as in Part III. In fact, since time t enters the equations for the distribution in either the grounded or isolated neutral case, merely as a cosine function, and since Duhamel's Theorem affects only the time function, the equations for the isolated-neutral case can be written immediately by inspection from the corresponding grounded-neutral equations for waves of arbitrary shape. The same conclusions and curves, concerning the effect of wave shape, apply to either case.

V. NEUTRAL IMPEDANCE

When a generalized impedance $Z\,(p)$ is inserted in the neutral of the transformer, the mathematical difficulties involved in attempting a solution become unsurmountable from an engineering point of view. An approximate method of solution which yields fair results is as follows:

1. Solve the equivalent circuit, Fig. 2, for the neutral voltage e_n.
2. Find the transient distribution due to the applied terminal voltage, on the assumption that the neutral is grounded.
3. Find the transient distribution due to the neutral voltage e_n on the assumption that the line terminal is grounded, using the grounded neutral equations and Duhamel's Theorem.
4. The resultant distribution is then given by adding the distributions found under (2) and (3).

The application of the above method will be illustrated for the case of a capacitance C_o in the neutral and for an infinite rectangular applied wave. In order to simplify the problem as much as possible, the capacitance $\sqrt{C K}$ will be neglected. Then the circuit consists of the surge impedance of the transmission line in series with L' and $C_n = C' C_o/(C' + C_o)$. By the theory of traveling waves the neutral voltage is

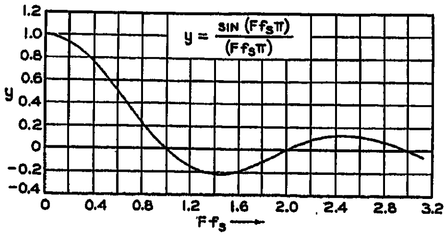

FIG. 8—HARMONIC REDUCTION FACTOR FOR WAVE FRONT

$$e_n = \frac{2/p\,C_n}{\frac{1}{p\,C_n} + p\,L' + z}\,E = 2\,E\,[1 - B\,\epsilon^{-at}\sin(b\,t + \theta)] \tag{1}$$

where

$$a = \frac{z}{2\,L'},\quad b = \sqrt{\frac{1}{L'\,C_n} - a^2},\quad B = \frac{1}{\sqrt{1 - a^2\,L'\,C_n}},$$

$$\theta = \tan^{-1}\left(\frac{b}{a}\right)$$

It will be sufficient to take the terminal voltage as 2 E. The solution corresponding to 2 E and grounded neutral is

$$e_1 = 2\,E\,x + 2\,E\sum_{1}^{\infty} A_s \sin s\,\pi\,x\,.\,\cos\omega_s\,t \tag{1}$$

Now considering the line end grounded, and the potential e_n applied at the neutral, the solution is, by Duhamel's theorem,

$$\begin{aligned} e_2 = (1 - x)\,e_n + 2\,E\sum_{1}^{\infty} A_s \sin s\,\pi\,(1 - x)\,\Bigg\{ & \cos\omega_s\,t \\ & - B\,\epsilon^{-at}\sin(b\,t + \theta) \\ & + B\,\frac{\omega_s^{\,2}\,\epsilon^{-at}}{(a^2 + b^2 + \omega_s^{\,2})^2 - 4\,b^2\,\omega_s^{\,2}}\,[2\,a\,b\cos(b\,t + \theta) \\ & + (b^2 - a^2 - \omega_s^{\,2})\sin(b\,t + \theta)\,] \\ & - B\,\frac{\omega_s}{2}\left[\frac{a\cos(\omega_s\,t + \theta) + (\omega_s - b)\sin(\omega_s\,t + \theta)}{a^2 + (b - \omega_s)^2}\right. \\ & \left. - \frac{a\cos(\omega_s\,t - \theta) + (b + \omega_s)\sin(\omega_s\,t + \theta)}{a^2 + (b + \omega_s)^2}\right]\Bigg\} \end{aligned} \tag{2}$$

Then by the principle of superposition, the actual resultant distribution is the sum of the distributions due to the terminal and neutral voltages, or

$$e = e_1 + e_2 \tag{3}$$

VI. CONTROL OF TRANSIENT DISTRIBUTION

In both the grounded and isolated neutral windings the transient distribution consists of an infinite series of space harmonics, the amplitudes of which are given by the Fourier analysis of the initial distribution with respect to the final distribution. It should not be inferred, however, that this is true for any generalized impedance in the neutral. When a neutral impedance is used there will be, in general, other transient terms than those given by the Fourier series, and such terms are not necessarily eliminated by making the initial and final distributions identical. The control of the transient distribution consists, then, in meeting the following two conditions:

A. Maintaining the neutral voltage constant during the abnormal voltage transient, for all applied wave shapes.

B. Elimination of the internal transient oscillations
  1. By making the initial and final distributions identical for an infinite rectangular wave, or
  2. By increasing the losses during the transient to such values that all oscillations are at least critically damped, or
  3. By modification of the applied wave shape.

Maintaining Constant Voltage at the Neutral. The only connection which will result in a perfectly constant neutral voltage under all conditions is the directly grounded neutral. However, if an isolated neutral or specified neutral impedance (such as a resistance or reactor) is necessary under normal operating conditions, then in order to simulate effectively the grounded-neutral condition during the transient, there are three means available:

1. A capacitance to ground with a charging period very long in comparison with the fundamental natural period of oscillation of the transformer, and with the length of the applied wave.
2. An oscillatory circuit with a period very long in comparison with the fundamental natural period of the transformer, and with the applied wave.
3. A resistance with an exaggerated negative characteristic which will effectively limit the rise of the neutral voltage.

Any of these or their combinations may be used provided that the proper functioning of the normal neutral impedance under the conditions for which it was intended is not interfered with.

However, while such impedances can be designed to hold the neutral voltage below a specified limit for any required length of time, yet the potential of the neutral rises by a slow transient.[4] This transient is approximately governed by the neutral impedance $Z(p)$, the transformer inductance L, and the surge impedance of the transmission line z. In accordance with the theory of traveling waves, the voltage at the transformer terminal, and the neutral voltage, corresponding to a traveling incident wave e on the transmission line, are respectively:

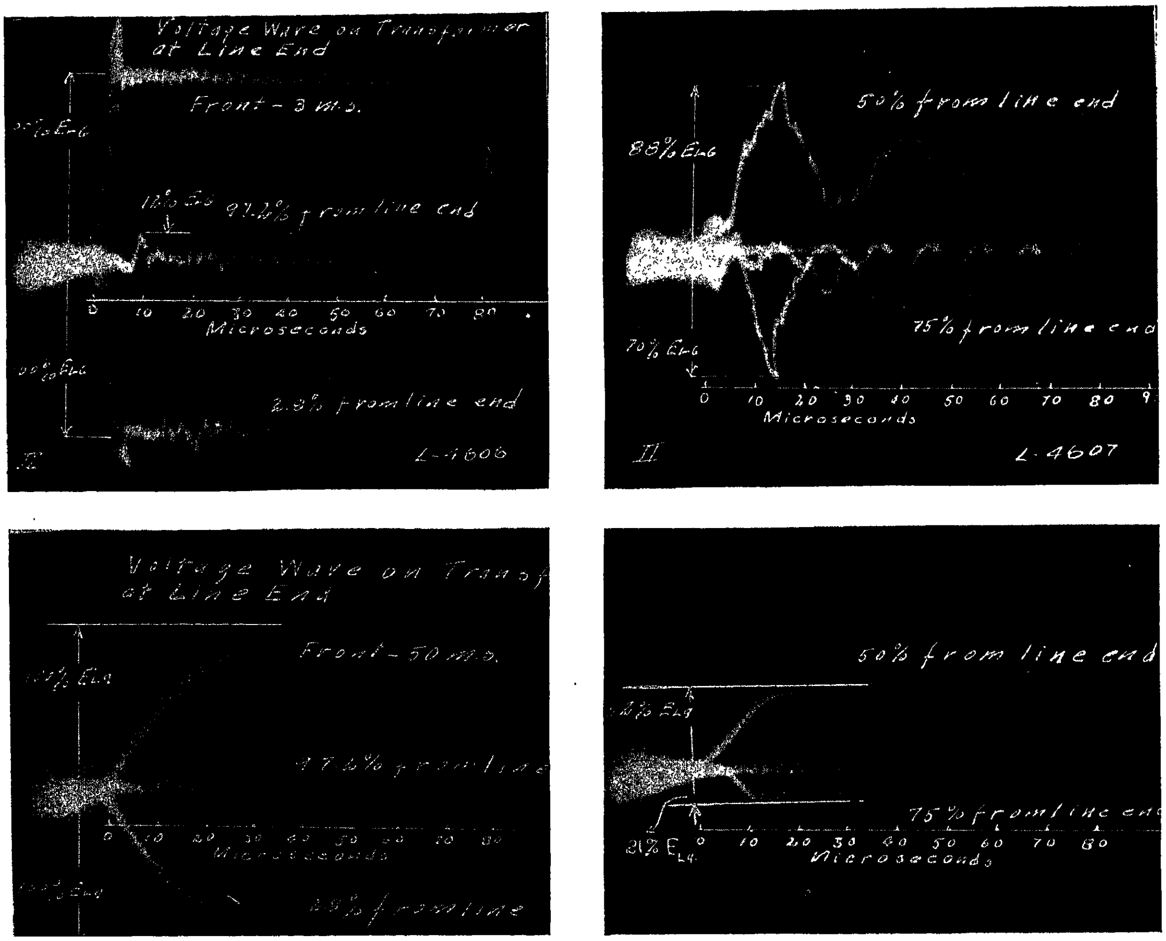

FIG. 9—EFFECT OF WAVE FRONT

Top, applied wave of 3-microsecond front
Bottom, applied wave of 50-microsecond front

$$e_1 = \frac{2\,[Z(p) + p\,L]}{Z(p) + p\,L + z}\,e(t)$$

$$e_n = \frac{2\,Z(p)}{Z(p) + p\,L + z}\,e(t)$$

Case I. $Z(p) = 1/p\,C_o$

For a capacitor in the neutral, and an infinite rectangular wave, there is

$$e_1 = 2\,E\left[1 - \frac{2\,\alpha}{\omega}\,\epsilon^{-\alpha t}\sin\omega\,t\right]$$

$$e_n = 2\,E\left[1 - \frac{\omega_o}{\omega}\,\epsilon^{-\alpha t}\sin\left(\omega\,t + \tan^{-1}\frac{\omega}{\alpha}\right)\right]$$

where

$$\alpha = z/2\,L$$

$$\omega_o^2 = 1/L\,C_o$$

$$\omega^2 = \omega_o^2 - \alpha^2$$

Thus the neutral voltage oscillates with a damped amplitude of practically 2 E about the 2 E line as an axis; so that the neutral voltage may rise to nearly four times the voltage of the incident wave for infinite rectangular wave excitation. Superimposed hereon are the internal high frequency oscillations, and if the fundamental natural frequency of the winding is in the neighborhood of that of the neutral, voltages of the order of three times the terminal voltage will be experienced at points in the winding. Of course, if the applied wave happens to be oscillatory with a near resonant frequency, then exceedingly high voltages will be built up and destruction of the apparatus may occur. For these reasons a capacitor by itself is not a sufficient guarantee that the neutral voltage will be controlled for all applied wave shapes and conditions.

Case IV. The Impedor

Another method of controlling the neutral voltage under transient conditions is by means of the impedor.[4] It consists, essentially of three elements: (1) the normal frequency neutral impedance, (2) a capacitor which is effective in holding down the neutral voltage for most lightning waves, and (3) a resistor having a decided negative characteristic in series with a gap, to take care of extremely long lightning waves, or arcing ground and switching surges. As an example of how the effects of such an impedor may be calculated by a tabular step-by-step method of successive approximations, let:

L_o = inductance of the normal-frequency neutral reactor
C_o = capacitance of the impedor
z = surge impedance of transmission line
e = incident wave
e_n = neutral voltage
i = total current in the neutral
i_L = current in the neutral reactor
i_C = current in the neutral capacitor
i_R = current in the neutral resistor

Then by traveling wave theory

$$2e - zi = L\frac{di}{dt} + e_n$$

$$L_o\frac{di_L}{dt} = e_n$$

$$C_o\frac{de_n}{dt} = i_C$$

$i_R = f(e_n)$ from the negative resistance characteristic.

Substituting increments for differentials and rearranging

$$\Delta i_L = \frac{e_n}{L_o}\Delta t$$

$$i_L = \sum \Delta i_L$$

$$\Delta i = \left(\frac{2e - zi - e_n}{L}\right)\Delta t$$

$$i = \sum \Delta i$$

$$i_C = (i - i_R - i_L)$$

$$\Delta e_n = \frac{i_C}{C}\Delta t$$

In the above equations the average values of the variables over the interval Δt are to be used. Hereby a step-by-step method of successive approximations may be followed as shown in the following table. Such a table is filled in lightly with pencil, and each figure arrived at is readjusted by trial until all of the conditions specified by the above equations are fulfilled to the required degree of accuracy.

Δt	t	$2e$	e_n	Δe_n	i_C	i_R	i_L	Δi_L	Δi	i	Zi
	0	2000	0		0	0	0			0	0
10				33				1	199		
	10	2000	33		198	0.1	1			199	60
10				91				3	166		
	20	2000	124		344	17	4			365	110
10				116				6	168		
	30	2000	240		343	170	10			523	158
10				83				9	154		
	40	2000	323		162	495	19			677	203

Elimination of Oscillations by Shielding. If the neutral is maintained at substantially zero potential during the transient, then the axis of oscillations is

$$e_{t=\infty} = E\frac{\sinh \beta x}{\sinh \beta}$$

where

$$\beta = \sqrt{\frac{rG}{1 + rg}}$$

r = series resistance in the winding
g = shunted conductance along the stack
G = conductance to ground

However, in a normal transformer β is so small that

$$e_{t=\infty} = E\frac{\sinh \beta x}{\sinh \beta} \cong E\frac{\beta x}{\beta} = Ex$$

The initial distribution is

$$e_{t=0} = E\frac{\sinh \alpha x}{\sinh \alpha}$$

where

$\alpha = \sqrt{C/K}$
C = capacitance to ground
K = series capacitance along stack

Evidently the initial and final distributions are identical if

$$\alpha = \beta \quad \text{or} \quad \frac{C}{K} = \frac{r\,G}{1 + r\,g}$$

and all transient oscillations vanish. It is then simply a question as to which of the two it is most feasible to adjust. In practise it has been found much better to modify the initial distribution to conform to the final distribution than the reverse, because the initial distribution causes an excessive concentration of stress near the line end. There are three ways in which this may be accomplished:

Case I.

The conventional method of electrostatic shielding as employed on non-resonating transformers is shown in Fig. 10B. The auxiliary capacitances C_1', C_2', C_3', etc., are designed so that they supply the charging current of the capacitances C to ground, thereby relieving the series capacitances K of that current. At any point x the potential of the winding above ground for a linear distribution is $x\,E$, and the voltage between this point and the line terminal is $(1 - x)\,E$. Therefore in order that C_x' may supply the charging current to C at point x there must be

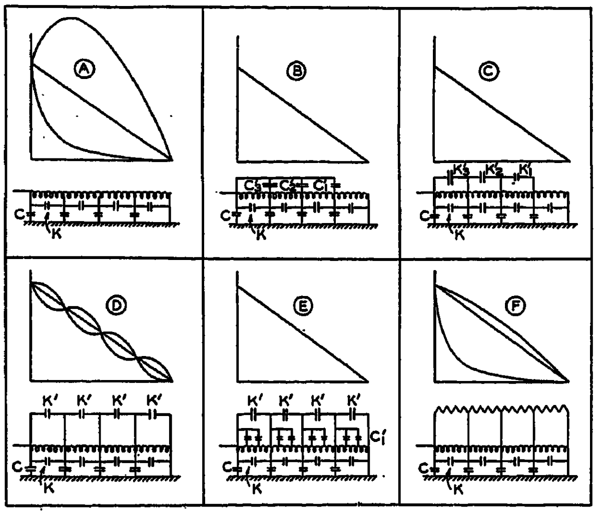

Fig. 10—Methods of Shielding

$$(1 - x)\,E\,C_x' = x\,\dot{E}\,C$$

$$\therefore C_x' = \frac{x}{1 - x}\,C$$

Consequently, the same current flows through the entire series capacitance path, K, and the distribution of voltage along the stack is linear. In effect, the ground capacitance C has been canceled or nullified by the shielding capacitance C', and therefore $\alpha = \sqrt{C/K} = 0$ and

$$e = E\,\frac{\sinh \alpha\,x}{\sinh \alpha} \cong E\,\frac{\alpha\,x}{\alpha} = E\,x$$

Case II.

Fig. 10C illustrates the method of shielding by means of auxiliary series capacitances K_1', K_2', K_3', etc. Suppose that the winding has been divided into n equal sections, and let the junctions be numbered 0, 1, 2, . . n from the neutral. Then for a linear distribution of voltage the conditions at junction x are

$$e = \frac{E}{n} = \text{voltage per section}$$

$$e_x = E\,\frac{x}{n} = \text{potential to ground}$$

$$E - e_x = \left(1 - \frac{x}{n}\right) E = \text{potential to the line terminal}$$

By Kirchhoff's law

$$\begin{aligned}
C\,e_x &= C\,e\,x = (K + K_x)\,e - (K + K'_{x-1})\,e \\
K_x' &= x\,C + K'_{x-1} \\
&= x\,C + (x - 1)\,C + K'_{x-2} \\
&= x\,C + (x - 1)\,C + (x - 2)\,C + K'_{x-3} \\
&\quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\
&= [x + (x - 1) + (x - 2) + \,.\,.\,.\,.\,.\, + 1]\,C + 0 \\
&= \frac{x\,(x + 1)}{2}\,C
\end{aligned}$$

Case III.

Increase K, by adding auxiliary series capacitances K' as shown in Fig. 10D to such an extent, that

$$\alpha = \sqrt{\frac{C}{K}} \to 0$$

$$E\,\frac{\sinh \alpha\,x}{\sinh \alpha} \cong E\,\frac{\alpha\,x}{\alpha} \doteq E\,x$$

The capacitance of the K' units can be made quite sufficient to give a practically linear initial distribution of the connected points, but since the sections of the winding between points are not equalized, local oscillations take place as shown in Fig. 10D. If it is desirable to suppress these local oscillations it may be effectively done by combining the schemes shown in Fig. 10B and Fig. 10D as indicated in Fig. 10E. Here the auxiliary capacitances (C_1', C_2', . . .) have been added to the circuit. There is a group for each section of the winding fed from the higher potential end of the section. The design is similar to that of Case I. Let points x_1 and x_2 be adjacent points on the winding maintained at the appropriate potentials $e_1 = x_1\,E$ and $e_2 = x_2\,E$ by the large auxiliary series capacitors K'. Let x be a point intermediate between x_1 and x_2 at which it is required to connect a capacitor C_x' such that the point x will be at potential $x\,E$. Then the voltage across C_x' is $(x_2 - x)\,E$, and therefore in order that C_x' may supply the charging current of the capacitance C of the winding to ground there must be

$$(x_2 - x)\, E\, C_x' = x\, E\, C$$

$$C_x' = \frac{x}{x_2 - x}\, C$$

It will be noticed in this scheme that the C_x' capacitances need not be insulated from the winding by more than the potential difference across one section of the winding, thus permitting a very economical type of shield to be used. However, the local oscillations in the individual sections are not dangerous, and ordinarily would not be compensated.

Elimination of Oscillations by Losses. In the general solution given in Appendix I it was shown that the effect of losses is threefold:

1. All harmonics suffer a decrement
2. The periods of oscillation are increased
3. Certain oscillations degenerate to exponential decay.

By increasing the losses sufficiently it is possible to prohibit all oscillations. The initial distribution then diffuses into the final distribution without over-shooting, and dangerous abnormal voltages are avoided. It may not be practicable to absolutely prohibit all oscillations, and a small amount of over-shooting may occur as shown in Fig. 10F. Perhaps the most simple method of controlling the distribution by losses is through the use of a tied-in shunt resistor. However, this shunt resistor must have such a low resistance to be effective against high-voltage surges, that its losses and heating under normal conditions become excessive, unless the material has a decided negative characteristic. Thyrite has been used to excellent advantage as a shunt resistor for current limiting reactors.[8]

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Appendix I

The General Differential Equation. Referring to Fig. 1, the circuit constants per unit length of winding are:

L = effective inductance including the mutual flux.
$M(x, y)$ = mutual inductance between elements at x and y.
C = shunt capacitance to ground.
K = series capacitance along the winding.
G = shunt conductance to ground.
g = shunt inductance along the winding.
r = series resistance.
n = turns.

The variables involved at any point of the winding are:

e = potential to ground.
i_1 = current in series capacitance K.
i_2 = current in the inductance L.
i_3 = current in the shunt conductance g.
i_4 = current to ground through G.
ϕ = total flux linkages at a point.
B = flux density.
t = time.
p = $\partial / \partial t$ = partial derivative with respect to time.
x, y = points along the winding, measured from the neutral end.
l = length of the winding.
$(m\, l\, t)$ = mean length of turn.
h = length of the leakage path.

The fundamental relationships are:

$$i_1 = K \frac{\partial^2 e}{\partial x\, \partial t} \tag{1}$$

$$i_3 = g \frac{\partial e}{\partial x} \tag{2}$$

$$i_4 = \left(G + C \frac{\partial}{\partial t}\right) e = \frac{\partial}{\partial x}\left(i_1 + i_2 + i_3\right) \tag{3}$$

$$\frac{\partial e}{\partial x} = r\, i_2 + \frac{n}{10^8} \frac{\partial \varphi}{\partial t} \tag{4a}$$

$$= r\, i_2 + \frac{\partial}{\partial t} \int_0^l M(x, y)\, i_2(y)\, .\, dy \tag{4b}$$

$$= r\, i_2 + \frac{\partial}{\partial t} \left\{ L' i_2(x) + \int_0^l M(x, y)\left[i_2(y) - i_2(x)\right] dy \right\} \tag{4c}$$

where

$$L' = \int_0^l M\,(x, y)\,d\,y = \text{self inductance}$$

$$\varphi = \varphi_m + \varphi_l = \varphi_m - (m\,l\,t)\int_0^x B_1\,d\,y + (m\,l\,t)\int_x^l B_2\,d\,y \tag{5}$$

where

φ_m = flux mutual to the entire winding.
φ_l = flux due to partial interlinkages.
B_1 = flux density for $0 < y < x$
B_2 = flux density for $x < y < l$

Assume, as simple approximation, that the flux density is distributed as a linear function

$$B_1 = \frac{-\,.4\,\pi\,n}{h}\int_x^l i_2\,(y)\,d\,y \tag{6}$$

$$B_2 = \frac{+\,.4\,\pi\,n}{h}\int_0^x i_2\,(y)\,d\,y \tag{7}$$

From (4a), (5), (6) and (7) there is

$$\frac{\partial^4 e}{\partial x^4} = r\,\frac{\partial^3 i_2}{\partial x^3} - \frac{.8\,\pi\,n^2(m\,l\,t)}{h\,10^8}\,\frac{\partial^2 i_2}{\partial x\,\partial t}$$

$$= r\,\frac{\partial^3 i_2}{\partial x^3} - \frac{L}{l^3}\,\frac{\partial^2 i_2}{\partial x\,\partial t} \tag{8}$$

where

$$L = \frac{.8\,\pi\,n^2\,l^3\,(m\,l\,t)}{h\,10^8} = \text{effective inductance}$$

By (1), (2), and (3) there is

$$\frac{L}{l^3}\,\frac{\partial^2 i_2}{\partial x\,\partial t} = \frac{L}{l^3}\left(G + C\,\frac{\partial}{\partial t}\right)\frac{\partial e}{\partial t}$$

$$- \frac{L}{l^3}\,\frac{\partial^2 i_1}{\partial x\,\partial t} - \frac{L}{l^3}\,\frac{\partial^2 i_3}{\partial x\,\partial t} = \frac{L}{l^3}\,G\,\frac{\partial e}{\partial t}$$

$$+ \frac{L}{l^3}\,C\,\frac{\partial^2 e}{\partial t^2} - \frac{L}{l^3}\,K\,\frac{\partial^4 e}{\partial x^2\,\partial t^2} - g\,\frac{L}{l^3}\,\frac{\partial^3 e}{\partial x^2\,\partial t} \tag{9}$$

and

$$r\,\frac{\partial^3 i_2}{\partial x^3} = r\,G\,\frac{\partial^2 e}{\partial x^2} + r\,C\,\frac{\partial^3 e}{\partial x^2\,\partial t} - r\,K\,\frac{\partial^5 e}{\partial x^4\,\partial t}$$

$$- g\,r\,\frac{\partial^4 e}{\partial x^4} \tag{10}$$

Substituting (9) and (10) in (8) there results

$$r\,K\,\frac{\partial^5 e}{\partial x^4\,\partial t} + (1 + g\,r)\,\frac{\partial^4 e}{\partial x^4} - \frac{L}{l^3}\,K\,\frac{\partial^4 e}{\partial x^2\,\partial t^2}$$

$$- \left(r\,C + g\,\frac{L}{l^3}\right)\frac{\partial^3 e}{\partial x^2\,\partial t} - r\,G\,\frac{\partial^2 e}{\partial x^2} + \frac{L}{l^3}\,C\,\frac{\partial^2 e}{\partial t^2}$$

$$+ \frac{L}{l^3}\,G\,\frac{\partial e}{\partial t} = 0 \tag{11}$$

If the losses can be neglected equation (11) reduces to

$$\frac{\partial^4 e}{\partial x^4} - \frac{L\,K}{l^3}\,\frac{\partial^4 e}{\partial x^2\,\partial t^2} + \frac{L}{l^3}\,C\,\frac{\partial^2 e}{\partial t^2} = 0 \tag{12}$$

Hereafter it will be convenient to take $l = 1$.

The total current is, from (3)

$$(i_1 + i_2 + i_3) = \left(G + C\,\frac{\partial}{\partial t}\right)\int e\,d\,x \tag{13}$$

The solution to these equations must satisfy

a. The differential equation
b. The terminal conditions at $x = 0$ and $x = l$
c. The initial distribution at $t = 0$
d. The final distribution at $t = \infty$

If the solution corresponding to a constant sustained potential suddenly applied at $x = l$ can be found, then the solution for any other applied terminal voltage is given by Duhamel's Theorem. The usual procedure in solving a partial differential equation is to assume the form of the solution and try it by direct substitution in the differential equation and the boundary conditions. Each tentative trial usually suggests the necessary changes and adjustments in order to meet the complete specifications. Therefore, in order to choose the proper solution from among the infinite number of functions which will satisfy the differential equations, it is necessary to first investigate the boundary conditions.

The Initial Distribution. When an infinite rectangular wave is applied at the terminal of the winding, the currents in the capacitances at the first instant are infinite, since the time rate of change of voltage is infinite; whereas the current in the inductive winding is zero, and in the resistances the currents are all finite. Therefore the initial distribution of potential depends only upon the capacitances, Fig. 1B, and can be determined by solving the differential equation for the capacitances alone. Consequently, considering only the capacitances of the circuit, the combination of equations (1) and (3) gives ($G = 0$).

$$\frac{\partial^2 e}{\partial x^2} - \frac{C}{K}\,e = \frac{\partial^2 e}{\partial x^2} - \alpha^2 e = 0 \tag{14}$$

where

$$\alpha = \sqrt{C/K}$$

This equation also follows from the general differential equation (11) upon dividing through by $p^2 = \partial^2/\partial t^2$ and putting $p = \infty$, according to the procedure in operational calculus.

The solution to (14) is:

$$e = A\,\epsilon^{\alpha x} + B\,\epsilon^{-\alpha x} \tag{15}$$

and from (1) the corresponding current is

$$i = K\,p\,\frac{\partial e}{\partial x} = K\,p\,\alpha\,(A\,\epsilon^{\alpha x} - B\,\epsilon^{-\alpha x}) \qquad (16)$$

where $p \to \infty$, and the initial rush of current is therefore infinite.

Suppose that the winding is grounded at $x = 0$ through a generalized impedance $Z\,(p)$, and that the voltage applied at $x = 1$ is E. Then

$$\left.\begin{aligned} &\text{at } x = 1,\ e = E = A\,\epsilon^{\alpha} + B\,\epsilon^{-\alpha} \\ &\text{at } x = 0,\ e = Z\,(p)\,i = Z(p)\,p\sqrt{C\,K}\,(A - B) = A + B \end{aligned}\right\} \qquad (17)$$

Herefrom the integration constants are

$$\left.\begin{aligned} A &= \frac{1}{2}\,\frac{[Z\,(p)\,p\,\sqrt{C\,K} + 1]\,E}{Z\,(p)\,p\,\sqrt{C\,K}\cosh\alpha + \sinh\alpha} \\ B &= \frac{1}{2}\,\frac{[Z\,(p)\,p\,\sqrt{C\,K} - 1]\,E}{Z\,(p)\,p\,\sqrt{C\,K}\cosh\alpha + \sinh\alpha} \end{aligned}\right\} \qquad (18)$$

and the initial distribution therefore is

$$e = E\,\frac{Z\,(p)\,p\,\sqrt{C\,K}\cosh\alpha\,x + \sinh\alpha\,x}{Z\,(p)\,p\,\sqrt{C\,K}\cosh\alpha + \sinh\alpha}\Bigg]_{p\,=\,\infty} \qquad (19)$$

For a grounded neutral $Z\,(p) = 0$ and

$$e = \frac{\sinh\alpha\,x}{\sinh\alpha}\,E \qquad (20)$$

For an isolated neutral, $Z\,(p) = \infty$ and

$$e = \frac{\cosh\alpha\,x}{\cosh\alpha}\,E \qquad (21)$$

For a capacitance C_o in the neutral $Z\,(p) = 1/p\,C_o$ and

$$e = \frac{\sqrt{C\,K}\cosh\alpha\,x + C_o\sinh\alpha\,x}{\sqrt{C\,K}\cosh\alpha + C_o\sinh\alpha}\,E$$

For an inductance L_o in the neutral $Z\,(p) = p\,L_o$ and

$$e = \frac{L\,p^2\,\sqrt{C\,K}\cosh\alpha\,x + \sinh\alpha\,x}{L\,p^2\,\sqrt{C\,K}\cosh\alpha + \sinh\alpha}\Bigg]_{p\,=\,\infty} E$$

$$= \frac{\cosh\alpha\,x}{\cosh\alpha}\,E \qquad (23)$$

Equation (19) may be expressed as a half-range sine series

$$e = 2\sum_{1}^{\infty}\sin s\,\pi\,x\int_{o}^{1} e\sin s\,\pi\,x\,d\,x$$

$$= E\sum_{1}^{\infty}\left\{\frac{p\,Z(p)\,\sqrt{CK}(1 - \cos s\,\pi\cosh\alpha) - \cos s\,\pi\sinh\alpha}{p\,Z(p)\,\sqrt{C\,K}\cosh\alpha + \sinh\alpha}\right\}$$

$$\frac{2\,s\,\pi}{\alpha^2 + s^2\,\pi^2}\sin s\,\pi\,x \qquad (24)$$

The Final Distribution. After the transient incident to the application of an infinite rectangular wave at the line terminals has died out (theoretically at $t = \infty$) the residual distribution is direct current. The capacitance elements then act as open circuits and the inductance elements as short circuits. The distribution is then entirely determined by the resistance elements, Fig. 1c. The differential equation for this circuit from (2), (3), and (4) is

$$\frac{\partial^2 e}{\partial x^2} - R\,G\,e = \frac{\partial^2 e}{\partial x^2} - \beta^2\,e = 0 \qquad (25)$$

where

$$R = \frac{r}{1 + g\,r} = \text{resistance of } r \text{ and } g \text{ in parallel}$$

and

$$\beta^2 = R\,G$$

This equation also follows from the general differential equation (11) upon substituting $p = \partial/\partial\,t = 0$ according to the procedure in operational calculus.

The solution to (25) is

$$e = A\,\epsilon^{\beta x} + B\,\epsilon^{-\beta x} \qquad (26)$$

and from (2) and (4) the corresponding current is

$$i = \frac{1}{R}\,\frac{\partial e}{\partial x} = \sqrt{\frac{G}{R}}\,(A\,\epsilon^{\beta x} - B\,\epsilon^{-\beta x}) \qquad (27)$$

The terminal conditions are

$$\left.\begin{aligned} &\text{at } x = 1,\ e = E = A\,\epsilon^{\beta} + B\,\epsilon^{-\beta} \\ &\text{at } x = 0,\ e = Z(p)\,i = Z(p)\sqrt{\frac{G}{R}}(A - B) = A + B \end{aligned}\right\} \qquad (29)$$

Herefrom the integration constants are

$$\left.\begin{aligned} A &= \frac{1}{2}\,\frac{[Z\,(p)\,\sqrt{G/R} + 1]\,E}{Z\,(p)\,\sqrt{G/R}\cosh\beta + \sinh\beta} \\ B &= \frac{1}{2}\,\frac{[Z\,(p)\,\sqrt{G/R} - 1]\,E}{Z\,(p)\,\sqrt{G/R}\cosh\beta + \sinh\beta} \end{aligned}\right\} \qquad (30)$$

and the final distribution therefore is

$$e = E\,\frac{Z\,(p)\,\sqrt{G/R}\cosh\beta\,x + \sinh\beta\,x}{Z\,(p)\,\sqrt{G/R}\cosh\beta + \sinh\beta}\Bigg]_{p\,\to\,0} \qquad (31)$$

For a grounded neutral or an inductance in the neutral $Z(p) = 0$ and

$$e = E\,\frac{\sinh\beta\,x}{\sinh\beta} \qquad (32)$$

For an isolated neutral or a capacitance in the neutral $Z\,(p) = \infty$ and

$$e = E\,\frac{\cosh\beta\,x}{\cosh\beta} \qquad (33)$$

For a resistance R_o in the neutral, $Z\,(p) = R_o$ and

$$e = E\,\frac{R_o\,\sqrt{G/R}\cosh\beta\,x + \sinh\beta\,x}{R_o\,\sqrt{G/R}\cosh\beta + \sinh\beta} \qquad (34)$$

In a normal machine β is a very small quantity, so that approximately, using only the first terms in the cosh and sinh series,

$$e = E\frac{Z\,(p)\,\sqrt{G/R} + \sqrt{R\,G}\,x}{Z\,(p)\,\sqrt{G/R} + \sqrt{R\,G}} = E\,\frac{Z\,(p) + R\,x}{Z\,(p) + R} \qquad (35)$$

SOLUTION FOR GROUNDED NEUTRAL

As a tentative solution to equation (11) assume

$$e = E\,\frac{\sinh \beta\, x}{\sinh\, \beta} + \sum A\, \epsilon^{ax+bt} \qquad (36)$$

The first term represents the axis of oscillations as given by equation (32) in which

$$\beta = \sqrt{\frac{r\,G}{1 + g\,r}}$$

and the summation term is the usual trial solution for a differential equation of this type. Substituting (36) in (11) there results

$$r\,K\,a^4\,b + (1 + g\,r)\,a^4 - L\,K\,a^2\,b^2 - (r\,C + g\,L)\,a^2\,b$$
$$- r\,G\,a^2 + L\,C\,b^2 + L\,G\,b = 0 \qquad (37)$$

Solving this equation for b there is

$$b = -\,\frac{r\,K\,a^4 - (r\,C + g\,L)\,a^2 + L\,G}{2\,L\,(C - K\,a^2)}$$

$$\pm\,\frac{\sqrt{(r\,K\,a^4 - r\,C\,a^2 - g\,L\,a^2 + L\,G)^2 - 4\,L(C - K\,a^2)(a^4 + g\,r\,a^4 - r\,G\,a^2)}}{2\,L\,(C - K\,a^2)}$$

$$= -\,\gamma \pm j\,\omega \qquad (38)$$

Write $\lambda^2 = -\,a^2$ or $a = \pm j\,\lambda$ so that (36) takes the form

$$e = E\,\frac{\sinh \beta\, x}{\sinh \beta} + \sum \epsilon^{-\gamma t}\,[A \sin \lambda\, x\,.\, \cos \omega\, t$$
$$+ B \sin \lambda\, x\,.\, \sin\, \omega\, t + C \cos \lambda\, x\,.\, \cos \omega\, t$$
$$+ D \cos \lambda\, x\,.\, \sin\, \omega\, t] \qquad (39)$$

Comparing this equation at $t = 0$ with equation (24) for the initial distribution it is evident that $C = 0$ and

$$\lambda = s\,\pi \qquad (40)$$

and the corresponding values of γ and ω are determined from (39). When $x = 1$, equation (40) gives

$$e = E + \sum \epsilon^{-\gamma t}\,(C \cos \omega\, t + D \sin\, \omega\, t) \cos s\, \pi \qquad (41)$$

and since $e = E$ at $x = 1$ it follows that $C = D = 0$. Therefore,

$$e = E\,\frac{\sinh \beta\, x}{\sinh \beta} + \sum_{s=1}^{\infty} \epsilon^{-\gamma_s t}\,(A_s \cos\, \omega_s\, t + B_s \sin\, \omega_s\, t)$$
$$\sin s\, \pi\, x \qquad (42)$$

The A_s coefficients are determined by a comparison with equation (20). Putting $t = 0$ in (42), equating to (25) and expressing the *sinh* as a half-range *sine* series there is

$$E \sum_{1}^{\infty} \frac{-\,2\,s\,\pi}{\beta^2 + \pi^2\,s^2} \cos s\,\pi \sin s\,\pi\,x + \sum_{1}^{\infty} A_s \sin s\,\pi\,x$$

$$= E \sum_{1}^{\infty} \frac{-\,2\,s\,\pi}{\alpha^2 + s^2\,\pi^2} \cos s\,\pi\,.\, \sin s\,\pi\,x \qquad (43)$$

Therefore

$$A_s = \frac{2\,s\,\pi\,(\cos s\,\pi)\,(\alpha^2 - \beta^2)}{(\beta^2 + s^2\,\pi^2)\,(\alpha^2 + s^2\,\pi^2)}\,E \qquad (44)$$

The coefficients B_s are zero, as is evident from the condition that the current i_2 through the inductance is zero for $t = 0$. Then the differential equation and the initial, final, and terminal conditions are all satisfied. Therefore the solution is

$$e = E\,\frac{\sinh \beta\, x}{\sinh \beta}$$

$$+ \mathrm{E} \sum_{1}^{\infty} \frac{2\,(-1)^s\,s\,\pi\,.\,(\alpha^2 - \beta^2)}{(\beta^2 + s^2\,\pi^2)\,(\alpha^2 + s^2\,\pi^2)}\,\epsilon^{-\gamma_s t} \cos\, \omega_s\, t \sin s\,\pi\,x \qquad (45)$$

If the losses are zero ($r = g = G = 0$), then $\beta = 0$ and equation (38) reduces to

$$b = \pm\,\frac{\sqrt{-4\;\,L(C - K\;\,a^2)a^4}}{2\,L(C - K\,a^2)} = \pm\,j\,\frac{\lambda^2}{\sqrt{L(C + K\,\lambda^2)}}$$

$$= \pm\,j\,\frac{s^2\,\pi^2}{\sqrt{L(C + K\,s^2\,\pi^2)}} = \pm\,j\,\omega_s \qquad (46)$$

and the solution for zero losses therefore is

$$e = E\,x + E \sum_{1}^{\infty} \frac{2 \cos s\,\pi}{s\,\pi}$$

$$\left(\frac{\alpha^2}{\alpha^2 + s^2\,\pi^2}\right) \sin s\,\pi\,x \cos \frac{s^2\,\pi^2\,t}{\sqrt{L(C + K\,s^2\,\pi^2)}} \qquad (47)$$

This equation cannot be obtained by a direct application of the Heaviside expansion theorem.

SOLUTION FOR ISOLATED NEUTRAL

As mentioned in the last section, the Heaviside expansion theorem breaks down when applied to the solution of the differential equation given in this Appendix as equation (12). The author wrote to Dr. E. J. Berg of Union College for an explanation of the failure of the theorem. In subsequent discussions between Dr. Berg and his associates, Dr. J. J. Smith pointed out that the Heaviside expansion theorem depends upon an expansion in terms of partial fractions, and that in the particular problem, functions are encountered which do not lend themselves to such an expansion. Professor S. J. Haefner then modified the procedure so that the solution could be obtained by operational methods closely allied to the Heaviside expansion theorem, but in certain respects more extended in scope. The following operational solution of equation (12) for the case of an isolated neutral is by Haefner's method, and is given here pending a more detailed and rigorous treatment by him.

Rewriting equation (12) symbolically

$$(D^4 - L\,K\,p^2\,D^2 + L\,C\,p^2)\,e = 0 \tag{48}$$

where $D = \partial/\partial\,x$ and $p = \partial/\partial\,t$.

The operational solution to (48) then is

$$e = A \sinh \lambda\,x + B \cosh \lambda\,x + A' \sinh \lambda'\,x + B' \cosh \lambda'\,x$$

where the roots of (48) with respect to D are

$$\left.\begin{aligned} \lambda &= \sqrt{\frac{L\,K\,p^2}{2}\left(1 - \sqrt{1 - \frac{4\,C}{L\,K^2\,p^2}}\right)} \\ \lambda' &= \sqrt{\frac{L\,K\,p^2}{2}\left(1 + \sqrt{1 - \frac{4\,C}{L\,K^2\,p^2}}\right)} \end{aligned}\right\} \tag{49}$$

The current is

$$i = C\int p\,e\,d\,x = C\,p\left[\frac{A \cosh \lambda\,x + B \sinh \lambda\,x}{\lambda} + \frac{A' \cosh \lambda'\,x + B' \sinh \lambda'\,x}{\lambda'}\right] \tag{50}$$

For an isolated neutral

$$\left.\begin{aligned} i &= 0 \text{ at } x = 0 \\ e &= E \text{ at } x = 1 \end{aligned}\right\} \tag{51}$$

Therefore the terminal conditions are satisfied by

$$\left.\begin{aligned} A &= A' = B' = 0 \\ B &= \frac{E}{\cosh \lambda} \end{aligned}\right\} \tag{52}$$

and the solution is

$$e = E\,\frac{\cosh \lambda\,x}{\cosh \lambda} \tag{53}$$

Now the partial fraction theorem gives

$$\frac{Y(\lambda)}{Z(\lambda)} = \sum_{s=1}^{\infty} \frac{Y(\lambda_s)}{Z'(\lambda_s)}\,\frac{1}{(\lambda - \lambda_s)}$$

$$= \frac{Y(0)}{Z(0)} + \sum_{1}^{\infty} \frac{Y(\lambda_s)}{\lambda_s\,Z'(\lambda_s)}\left(\frac{\lambda}{\lambda - \lambda_s}\right) \tag{54}$$

where λ_s are the roots of $Z(\lambda) = 0$. Applying (54) to (53) there is

$$Z(\lambda) = \cosh \lambda = \prod_{s=1}^{\infty}\left[1 + \frac{4\,\lambda^2}{(2\,s - 1)^2\,\pi^2}\right] \tag{55}$$

$$\therefore \lambda_s = \pm\,j\,(2\,s - 1)\,\frac{\pi}{2} \tag{56}$$

$$Z'(\lambda_s) = \frac{d\,Z(\lambda)}{d\,\lambda}\Big]_{\lambda = \lambda_s} = \sinh(\lambda_s) = \pm\,j \sin(2\,s - 1)\,\frac{\pi}{2} \tag{57}$$

$$Y(\lambda_s) = E \cosh \lambda_s\,x = E \cos(2\,s - 1)\,\frac{\pi\,x}{2} \tag{58}$$

Therefore, using both forms of (54) there is

$$\begin{aligned} e ={}& - 2\,E \sum_{1}^{\infty} (-1)^s \cos(2\,s - 1)\frac{\pi\,x}{2}\left(\frac{(2\,s - 1)\,\pi/2}{\lambda^2 + (2\,s - 1)^2\,\dfrac{\pi^2}{4}}\right) \\ ={}& E + 2E \sum_{1}^{\infty} (-1)^s \frac{\cos(2\,s - 1)\,\pi\,x/2}{(2\,s - 1)\,\pi/2}\left(\frac{\lambda^2}{\lambda^2 + (2\,s - 1)^2\,\dfrac{\pi^2}{4}}\right) \end{aligned} \tag{59}$$

from which the half-range cosine series for E is easily obtained.

$$E = - 2\,E \sum_{1}^{\infty} (-1)^s\,\frac{\cos(2\,s - 1)\,\pi\,x/2}{(2\,s - 1)\,\pi/2} \tag{60}$$

Substituting (59) in (48) and making use of (60)

$$\lambda^2 = \frac{L\,C\,p^2}{(2\,s - 1)^2\,\dfrac{\pi^2}{4} + L\,K\,p^2} \tag{61}$$

so that (59) becomes

$$\begin{aligned} e ={}& E + 2\,E \sum_{1}^{\infty} (-1)^s\,\frac{\cos(2\,s - 1)\,\pi\,x/2}{(2\,s - 1)\,\pi/2}\left(\frac{C}{C + K\,(2\,s - 1)^2\,\pi^2/4}\right)\left(\frac{p^2}{p^2 + \omega_s^2}\right) \\ ={}& E + 2\,E \sum_{1}^{\infty} (-1)^s\,\frac{\cos(2\,s - 1)\,\pi\,x/2}{(2\,s - 1)\,\pi/2}\,\frac{\alpha^2}{\alpha^2 + (2\,s - 1)^2\,\pi^2/4}\cos \omega_s\,t \end{aligned} \tag{62}$$

where

$$\omega_s = \frac{(2\,s - 1)^2\,\pi^2/4}{\sqrt{L\,C + L\,K\,(2\,s - 1)^2\,\pi^2/4}} \tag{63}$$

Appendix II

NEGLIGIBLE MUTUAL INDUCTANCE AND NO LOSSES

The fundamental circuit equations are

$$i_1 = K\,\frac{\partial^2\,e}{\partial\,x\,\partial\,t} \tag{1}$$

$$i_4 = C.\frac{\partial\,e}{\partial\,t} = \frac{\partial}{\partial\,x}\,(i_1 + i_2) \tag{2}$$

$$\frac{\partial\,e}{\partial\,x} = L\,\frac{\partial\,i_2}{\partial\,t} \tag{3}$$

From these three equations the differential equation is

$$K L \frac{\partial^4 e}{\partial x^2 \partial t^2} + \frac{\partial^2 e}{\partial x^2} - L C \frac{\partial^2 e}{\partial t^2} = 0 \qquad (4)$$

or substituting $p = \partial / \partial t$ and rewriting in symbolic notation

$$\frac{\partial^2 e}{\partial x^2} - \frac{L C p^2}{K L p^2 + 1} e = 0 \qquad (5)$$

The solution to (5) with respect to x is

$$e = A \epsilon^{\sigma x} + B \epsilon^{-\sigma x} \qquad (6)$$

where

$$\sigma = \sqrt{\frac{L C p^2}{K L p^2 + 1}} \qquad (7)$$

From (2) and (6) the total current in the series path is

$$i = (i_1 + i_2) = \int C \frac{\partial e}{\partial t} d x = \frac{C p}{\sigma} (A \epsilon^{\sigma x} - B \epsilon^{-\sigma x}) \qquad (8)$$

The terminal conditions are

$$\left. \begin{aligned} e &= E \text{ at } x = 1 \\ Z(p)\, i &= e \text{ at } x = 0 \end{aligned} \right\} \qquad (9)$$

From (6), (8) and (9) the integration constants are

$$\left. \begin{aligned} A &= \frac{C p Z(p) + \sigma}{C p Z(p) \cosh \sigma + \sigma \sinh \sigma} \frac{E}{2} \\ B &= \frac{p Z(p) - \sigma}{C p Z(p) \cosh \sigma + \sigma \sinh \sigma} \frac{E}{2} \end{aligned} \right\} \qquad (10)$$

and substituting (10) in (6) there is

$$e = \frac{C p Z(p) \cosh \sigma x + \sigma \sinh \sigma x}{C p Z(p) \cosh \sigma + \sigma \sinh \sigma} E = \frac{Y(p)}{H(p)} \qquad (11)$$

This operational equation may be solved by the Heaviside expansion theorem

$$e = \frac{Y(p)}{H(p)} = \frac{Y(o)}{H(o)} + \sum \frac{Y(p_s) \epsilon^{p_s t}}{p_s H'(p_s)} \qquad (12)$$

where the summation is to include all of the roots of $H(p) = 0$

Applying (12) to (11) there is

$$Y(p) = C p Z(p) \cosh \sigma x + \sigma \sinh \sigma x \qquad (13)$$

$$H(p) = C p Z(p) \cosh \sigma + \sigma \sinh \sigma \qquad (14)$$

$$\frac{Y(o)}{H(o)} = \frac{Z(o) + p L x}{Z(o) + p L} \Big/_{p=0} \qquad (15)$$

The roots of (14) are given by the transcendental equation

$$\tanh \sigma = - \frac{C p Z(p)}{\sigma} \qquad (16)$$

and from (7)

$$p = \pm \sqrt{\frac{\sigma^2}{L (C - \sigma^2 k)}} \qquad (17)$$

In the general case, the roots of (16) must be found by methods of approximation.

$$p \frac{d H(p)}{d p} \Big/_{p=p_s} = \left(\sinh \sigma + \frac{\sigma}{\cosh \sigma} \right) \sigma \left(1 - \frac{\sigma^2}{\alpha^2} \right)$$

$$+ p_s \cosh \sigma C \frac{d}{d p} [p Z(p)]_{p=p_s} \qquad (18)$$

This is as far as the generalization can be carried.

If the neutral impedance is a capacitance C_o then

$$Z(p) = \frac{1}{p C_o} \qquad (19)$$

and the last term of (18) vanishes. Now substituting $\sigma = j \zeta$ equation (16) becomes

$$\frac{C_o}{C} \zeta = \cot \zeta = \frac{1}{\zeta} - \frac{\zeta}{3} - \frac{\zeta^3}{45}$$

$$- \frac{2}{945} \zeta^5 - \frac{\zeta^7}{4725} - \ldots \qquad (20)$$

or

$$\zeta^8 + 10 \zeta^6 + 105 \zeta^4 + \left(1575 - 4725 \frac{C_o}{C} \right) \zeta^2 - 4725 \cong 0$$

from which the most important roots of (16) may be determined by approximations. Suppose that this has been done for a specific ratio C_o/C. Then by (17)

$$p = \pm \frac{j \zeta}{\sqrt{L (C + \zeta^2 K)}} = \pm j \omega \qquad (21)$$

Substituting (13), (15), (18) and (21) in the expansion formula (12) there results,

$$e = E - 2 E \sum \frac{C \cos \zeta x - C_o \zeta \sin \zeta x}{C_o \left(\sin \zeta + \frac{\zeta}{\cos \zeta} \right) \zeta \left(1 + \frac{\zeta^2}{\alpha^2} \right)} \cos \omega t \qquad (22)$$

where the roots are given by equation (20).

For a grounded neutral, $Z(p) = 0$ and (16) gives

$$\sinh \sigma = \sigma \prod_1^\infty \left(1 + \frac{\sigma^2}{s^2 \pi^2} \right) = 0 \qquad (23)$$

from which

$$\sigma = \pm j \zeta = \pm j s \pi \qquad (24)$$

and the solution is

$$e = x E + E \sum_1^\infty \frac{\cos s \pi}{s \pi}$$

$$\frac{2 \alpha^2}{\alpha^2 + s^2 \pi^2} \sin s \pi x \cos \frac{s \pi t}{\sqrt{L (C + s^2 \pi^2 K)}} \qquad (25)$$

For an isolated neutral, $Z(p) = \infty$, and (**16**) gives

$$\cosh\sigma = \prod_{1}^{\infty}\left[1 + \frac{4\,\sigma^2}{\pi^2\,(2\,s - 1)^2}\right] = 0 \qquad (26)$$

from which

$$\sigma = \pm\,j\,\zeta = \pm\,j\,\frac{(2\,s - 1)\,\pi}{2} \qquad (27)$$

and the solution is

$$e = E + E\sum_{1}^{\infty}\frac{\sin s\,\pi/2}{s\,\pi}\,\frac{16\,\alpha^2}{s^2\,\pi^2 + 4\,\alpha^2}\cos\frac{s\,\pi\,x}{2}\cos\frac{s\,\pi\,t}{\sqrt{L\,(4\,C + K\,s^2\,\pi^2)}} \qquad (28)$$

when $K = 0$ and $\alpha = \sqrt{C/K} \to \infty$, this equation reduces to the equation of an open end transmission line, or

$$e = E + 4\,E\sum_{1}^{\infty}\frac{\sin s\,\pi/2}{s\,\pi}\cos\frac{s\,\pi\,x}{2}\cos\frac{s\,\pi\,t}{2\sqrt{L\,C}} \qquad (29)$$

The Heaviside expansion formula may be used for solving equation (**11**), whereas the method fails when applied to the differential equation of Appendix I (which includes mutual inductance). For this reason it is feasible to use the less general equations of this Appendix II when investigating the effect of neutral impedances. The suggestion is offered as an alternative to the method described under Part V of the paper.

Field Transients in Magnetic Systems

A Study of Field Transients in Iron Cores Partially Laminated and Partially Solid

BY ERNST WEBER*

Associate, A. I. E. E.

Synopsis.—The complete mathematical solution of applying suddenly a d-c. voltage to an electromagnetic circuit composed of an electric coil with a partly laminated and partly solid iron core containing an air-gap is presented in this paper. Starting from Maxwell's field equations for the eddy currents and the magnetic field in the iron core, the solution of the time conditions is reached with the aid of Heaviside's operational calculus. The result is expressed by means of a time constant of the magnetic field, composed of the time constant of the electric circuit and a fraction of a new-defined time constant of the solid iron part due to the eddy currents in that part. The importance of this result is illustrated by its application to a numerical example and to the effectiveness of quick response excitation in the case of large synchronous generators. Finally some other important applications are discussed.

I. INTRODUCTION

When switching an electric circuit on or off without an iron core or with an iron core of constant permeability and infinitely thin laminations, the current and the field (the magnetic flux may be designated shortly by the word "field," while the vectors of the magnetic field H and B may be called magnetic field strength and magnetic induction, respectively) have the same form of time variation,[1] *i.e.*, the same "time constant," by which the exponential curve can be easily characterized. In the case of a solid iron core, eddy currents arise when any change of the exciting current occurs, due to the law of induction. This case was generally treated[2,3,4] as a special problem of the decay of a magnetic field when switching off the circuit rather than considering the true condition of the interlinkage of the eddy currents with the exciting current. In this case of the special problem the time constant of the decreasing magnetic field may be defined.[5]

A further investigation of this subject lead to the solution of a periodically alternating field in a magnetic circuit with solid iron core.[6] This treatment also neglected the interlinkage of the eddy currents and the exciting current. Later the effect of the eddy currents was replaced by a secondary electric circuit.[7] In this case the solution was obtained as in the treatment of coupled electric circuits. This method of solution is given to avoid the use of the field equations, but the results with respect to the magnetic time constant are not sufficiently accurate.

Having the solutions of the decay of a magnetic field and that of an electric current separately and without interconnection, the problem is, how to combine the time constants to get the real time constant of the magnetic field in cases where finite changes take place and the interlinkage of the eddy currents with the exciting current cannot be neglected. It might be supposed that the arithmetic addition of the time constants would be a satisfactory approximation; but this paper proposes to show that this method of treatment leads to large error. This cannot be readily proven by experimental procedure, because there are so many influencing factors.

This matter is very important in certain practical applications of electrical engineering. The need of a general mathematical solution is, therefore, necessary. Probably the mathematical difficulties have precluded the solution heretofore. But in Heaviside's operational calculus[8,9] a very convenient and useful method is made available to extend the field of solutions.

II. MATHEMATICAL SOLUTION OF SWITCHING ON AN ELECTRIC CIRCUIT HAVING A PARTLY LAMINATED AND PARTLY SOLID IRON CORE CONTAINING AN AIR-GAP

1. Mathematical Statement by Maxwell's Field Equations. To obtain a mathematical solution of the proposed problem, it is not necessary to consider the complicated magnetic structure of an actual generator but rather assume the relatively simple case of a torroidal iron core containing an air-gap of length δ. The iron core itself consists of a solid part of length l_s and a laminated part of length l_l as shown in Fig. 1 and Fig. 1A. The excitation is given by an electric circuit connected to a d-c. voltage source.

There are three circuits to be considered, two electric circuits, the exciting coil and the eddy current circuit in the solid core, both interlinked by the magnetic circuit. When switching on the d-c. voltage, it is assumed that no eddy currents will occur in the laminated part due to the thinness of the laminations. But in the solid iron part eddy currents will appear which will oppose the increase of the magnetic field.

The mathematical statements for the switching phenomenon will be given in the so-called practical units, which means that the magnetic field strength is measured in amperes per centimeter, the electric field

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*Polytechnic Institute of Brooklyn, Brooklyn, N. Y.

1. For references see Bibliography.

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strength in volts per centimeter, the absolute permeability constant Π in farads per centimeter,[10] and the electric conductivity Λ in mhos per centimeter. For convenience it is assumed that Π is a constant quantity not only with reference to the cross-section of the solid iron part but also with respect to time. The influence of temperature on the eddy currents as well as on the electric current will be neglected.

It would be possible to start from Maxwell's field equations directly in the differential form. But it is more convenient and desirable to establish the equations in the integral form.[11,12] The electric current through the coil produces the magnetic field not only through the iron core but also in the surrounding air. So the total magnetic flux Φ can be subdivided, for convenience, into Φ_i, the flux in the iron core, as it would be measured by any loop situated as shown in Fig. 1, and into the leakage flux Φ_a, which can be assumed proportional to the current. Under these assumptions we get for the electric circuit, summing up the voltage drops and equalizing them to the impressed voltage V, the following differential equation:

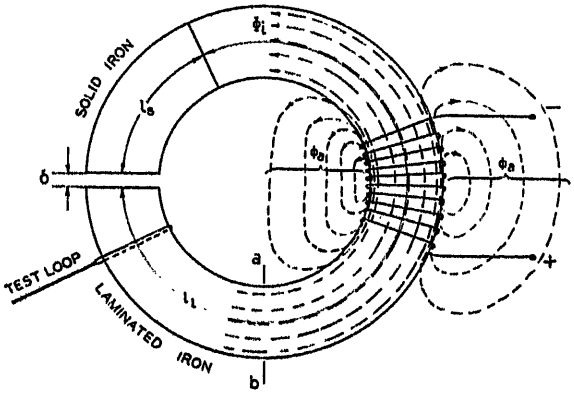

Fig. 1—The Toroidal Iron Core with Solid and Laminated Part and With Air Gap

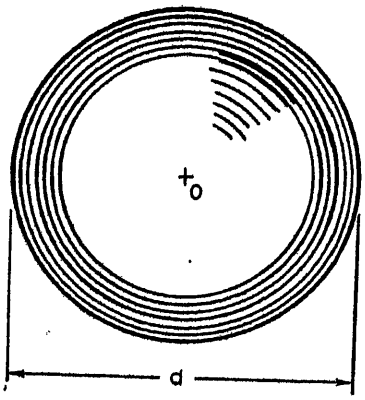

Fig. 1a—Showing the Lamination of the Laminated Iron Core

Section through a-b

$$R\,i + S\,\frac{d\,i}{d\,t} + N\,.\,\frac{d\,\Phi_i}{d\,t} = V, \tag{1}$$

in which S means the leakage inductance, and N designates the number of turns of the exciting coil.

The flux in the iron core is composed of two components. The first component, the flux density or magnetic induction $B_1 = \Pi_0\,H_1$, with the air-gap field strength H_1, is produced by the exciting current. The second component, the flux density or magnetic induction $B_2 = \Pi_0\,H_2$, with the air-gap field strength H_2, arises from the eddy currents in the solid part of the iron core. The total flux in the iron core is given by the integral over the cross-section

$$\Phi_i = \Pi_0 \iint_A (H_1 + H_2)\,.\,d\,A \tag{2}$$

The field strength H_1 is connected with the electric current by the closed line integral

$$\oint H_1\,d\,l = N\,.\,i\,. \tag{3}$$

Since H_1 designates the field strength in the air-gap in amperes per centimeter, we get the part of the integral given by the air-gap as $\delta\,H_1$, whereas the part of the integral due to the iron path is given by $\frac{l-\delta}{\mu}\,.\,H_1$ where μ designates the relative permeability of the iron. Introducing these expressions in (3) we get, abbreviating

$$\left(\delta + \frac{l-\delta}{\mu}\right).\,H_1 = l'\,.\,H_1 = N\,.\,i, \tag{3a}$$

in which l' is the equivalent length of the iron core and air-gap. The field strength produced by the eddy currents and its interlinkage with these currents is expressed by a similar equation in which the left hand term gives the difference of the two line integrals shown in Fig. 2, and in which the right hand term gives the enclosed amount of eddy currents. If the density of these eddy currents is designated by G, the line integral equation becomes,

$$l'\,.\,H_2(r) - l'\,.\left[H_2(r) + \frac{\partial H_2}{\partial r}\,.\,d\,r\right]$$
$$= \iint_A G\,.\,d\,A = l_s\,.\,G\,.\,d\,r\,. \tag{4}$$

From this we get the differential equation

$$\frac{\partial H_2}{\partial r} = -\,\frac{l_s}{l'}\,.\,G = -\,\frac{l_s}{l'}\,.\,\Lambda\,E, \tag{4a}$$

in which E = the electric field strength due to the eddy currents according to Ohm's Law. The eddy currents are produced by the change of magnetic field in the solid iron part. The law of induction applied to the solid iron part gives (refer to Fig. 2A)

$$\oint E\,.\,d\,s = -\,\frac{\partial}{\partial t}\iint B\,.\,d\,A \tag{5}$$

Since we have no variation of the quantities E and B with the angle φ, we may then write

$$2\,r\,\pi\,E = -\frac{\partial}{\partial t}\,(2\,\pi\,.\int\limits_{r=0}^{r} r\,B\,d\,r)\,.$$

By differentiating the above equation with respect to r we get, remembering $B = \Pi_0\,(H_1 + H_2)$,

$$\frac{\partial}{\partial r}\,(r\,E) = -\,r\,\Pi_0\,.\,\frac{\partial}{\partial t}\,(H_1 + H_2)\,. \qquad \textbf{(5a)}$$

The differential equations (**1**), (**2**), (**3a**), (**4a**) and (**5a**) give the mathematical statement of the entire problem.

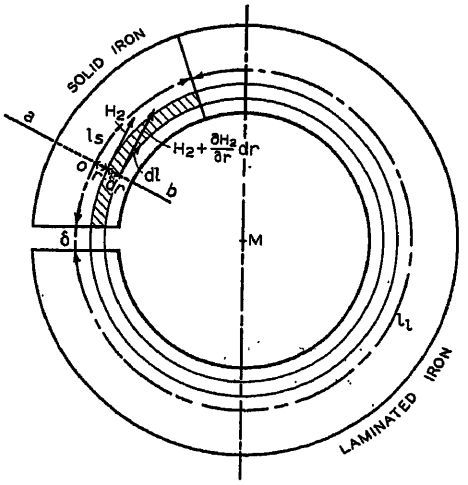

FIG. 2—REPRESENTING THE LINE INTEGRAL OF THE MAGNETIC FIELD STRENGTH

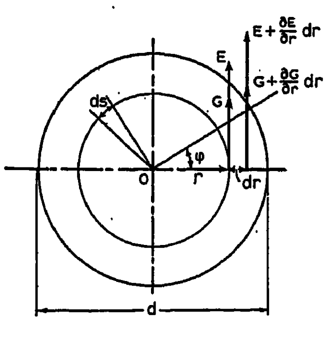

FIG. 2A—SHOWING VIEW A-B FROM FIG. 2 AND THE CYLINDRICAL COORDINATE SYSTEM

2. Introduction of Heaviside's Notation; the Differential Equation for the Magnetic Field Strength Due to the Eddy Currents. The differential equation for the magnetic field strength due to the eddy currents is derived from the combination of the above five general equations into one equation containing only the function H_2. In doing this, the most convenient method is the application of Heaviside's notation by which the time variation may temporarily be eliminated, leaving only the radius r as the variable.

Proceeding in the elimination from the above equations to obtain the final differential equation, let us combine equations (**4a**) and (**5a**) to give,

$$\left[\frac{\partial^2 H_2}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial H_2}{\partial r}\right] = \frac{l_s}{l'}\,.\,\Lambda\,\Pi_0\,.\,\frac{\partial}{\partial t}\,(H_1 + H_2) \qquad \textbf{(6)}$$

The partial derivatives with respect to time may be replaced by the total derivatives, because all circuits are relatively at rest.

Introducing Heaviside's notation of his operational calculus,[8,9] we may replace the total differentiations with respect to time by the symbol p. Beginning with equation (**1**), we write it in the form

$$(R + p\,S)\,.\,i = V\,.\,1 - N\,p\,\Phi_i\,. \qquad \textbf{(7)}$$

The symbol 1 designates Heaviside's unit function. Introducing for the above flux Φ_i, its value from equation (**2**), we now have separated the two magnetic field strengths. Since H_1 depends only on the current and is constant over the entire cross-section, we may integrate this expression over the cross-section and replace H_1 from equation (**3a**). Doing this we obtain

$$(R + p\,S)\,i = V\,.\,1 - N\,p\,\Pi_0\cdot\frac{d^2\,\pi}{4}\cdot\frac{N}{l'}\,i$$
$$-\,N\,p\,\pi_0\iint\limits_A H_2\,d\,A\,. \qquad \textbf{(7b)}$$

The product of the magnetic flux due to H_1 and the number of turns is identical with $L_0\,i$, where L_0 stands for the fictitious inductance (without eddy currents) of the flux in the iron core produced by H_1. Introducing this expression in (**7b**) and shifting all terms proportional to the current to the left hand side, we get

$$(R + p\,S + p\,L_0)\,i = V\,.\,1 - N\,p\,\Pi_0\iint H_2\,d\,A$$

from which the operational solution of the current is

$$i = \frac{V\,.\,1 - N\,p\,\Pi_0\,.\iint H_2\,.\,d\,A}{R + p\,S + p\,L_0}\,. \qquad \textbf{(8)}$$

We may indicate the denominator by the symbol P as the transient impedance of the electric circuit:

$$P = R + p\,(L_0 + S). \qquad \textbf{(9)}$$

Hence,

$$i = \frac{V}{P}\,1 - \frac{N\,\Pi_0}{P}\cdot p\iint\limits_A H_2\,d\,A\,. \qquad \textbf{(10)}$$

In order to eliminate H_1 of equation (**6**) substitute i of equation (**10**) in equation (**3a**). Writing this in operational form gives the final differential equation for the magnetic field strength due to the eddy currents, as

$$\left[\frac{d^2 H_2}{d\,r^2} + \frac{1}{r}\cdot\frac{d\,H_2}{d\,r} - \frac{l_s}{l'}\cdot\Lambda_0\,\Pi.\,p\,H_2\right]$$
$$= \frac{l_s}{l'^2}\cdot\frac{\Lambda\,\Pi_0\,p\,N}{P}\cdot\left[V\,.\,1 - 2\,r\,N\,\Pi_0\,.\,p\int\limits_{r=0}^{d/2} H_2\,d\,r\right] \qquad \textbf{(11)}$$

3. The Operational Solution for the Magnetic Field and the Electric Current. The left hand side of equation (11) is a differential equation in r leading to the special solution for the magnetic field strength H_2. The right hand side is merely a function of the time, not dependent on r. Therefore, the total solution of (11) may be given as the sum of the solution of the so-called homogeneous differential equation:

$$\frac{d^2 H_2}{d r^2} + \frac{1}{r}\frac{d H_2}{d r} - \frac{l_s}{l'} \cdot \Lambda \Pi_0 \, p \, H_2 = 0 \tag{12}$$

and a partial integral of (11) as any arbitrary function of p. The general solution of (12) is easily given in terms of Bessel functions of the first order and of the first two kinds[13,14]

$$H_2' = C \, . \, J_0 (K r) + D \, . \, N_0 (K r) \, , \tag{13}$$

in which C and D are arbitrary constants of integration. Introducing this solution in (12) we get

$$K = \sqrt{- \frac{l_s}{l'} \, . \, \Lambda \Pi_0 p} = j \sqrt{\frac{l_s}{l'} \, . \, \Lambda \Pi_0} \, . \, \sqrt{p}. \tag{14}$$

The partial integral as a single function of p may be written as,

$$H_2'' = F(p) \, . \tag{15}$$

The composition of (13) and (15) gives as the total solution

$$H_2 = H_2' + H_2'' = C \, J_0 (K r) + D \, N_0 (K r) + F(p). \tag{16}$$

To determine the integration constants C and D and the arbitrary function $F(p)$ we have first two boundary conditions to introduce. At $r = 0$, the electric field strength of the eddy currents disappears, because we have a circular current. At $r = \frac{d}{2}$, the magnetic field strength of the eddy currents must disappear, because beyond $r = \frac{d}{2}$ there are no eddy currents.

Introducing equation (16) into (4a) gives

$$E = - \frac{l'}{l_s} \cdot \frac{1}{\Lambda} \cdot \frac{d H_2}{d r}$$

$$= - \frac{l'}{l_s} \cdot \frac{1}{\Lambda} [- C K r J_1 (K r) - D K r N_1 (K r)]$$

From the first boundary condition putting r equal to zero, $J_1 (o) = 0$ and $N_1 (o) = \infty$. Therefore, D must equal zero,

$$D = 0 \tag{17}$$

Observing (17) we get by the second boundary condition

$$H_2 \Big|_{r = \frac{d}{2}} = C \, . \, J_0 \left(K \frac{d}{2} \right) + F(p) = 0$$

and from this

$$C = - \frac{F(p)}{J_0 \left(K \frac{d}{2} \right)} , \tag{18}$$

so that we now have from equation (16),

$$H_2 = F(p) \, . \left[1 - \frac{J_0 (K r)}{J_0 \left(K \frac{d}{2} \right)} \right] . \tag{19}$$

The solution (19) entered in (11) must satisfy this fundamental equation. The required integral $\int_{r=0}^{d/2} H_2 \, r \, d r$ in (11) may now be solved with the aid of (19), giving

$$\int_{r=0}^{d/2} H_2 \, r \, d r$$

$$= F(p) \cdot \frac{d^2}{8} \cdot \left[1 - 2 \frac{J_1 \left(K \frac{d}{2} \right)}{\left(K \frac{d}{2} \right) J_0 \left(K \frac{d}{2} \right)} \right] . \tag{20}$$

Introducing now (19) and (20) in (11), gives

$$F(p) \left\{ \frac{d^2 \pi}{4} \cdot \Pi_0 \, . \, p \, N \left[1 - 2 \frac{J_1 \left(K \frac{d}{2} \right)}{\left(K \frac{d}{2} \right) J_0 \left(K \frac{d}{2} \right)} \right] - \frac{l'}{N} P \right\} = V . 1$$

and, therefore, the arbitrary function $F(p)$ by the operational expression becomes

$$F(p) = \frac{N}{l'} \cdot \frac{V}{p \, L_0 \left[1 - \frac{2 J_1 \left(K \frac{d}{2} \right)}{\left(K \frac{d}{2} \right) J_0 \left(K \frac{d}{2} \right)} \right] - P} \cdot 1 \tag{21}$$

Replacing (21) in (19) and simplifying gives the final operational solution for the magnetic field strength in the form

$$H_2 = \frac{N}{l'} .$$

$$\frac{-K\frac{d}{2}\cdot\left[J_0\left(K\frac{d}{2}\right)-J_0(Kr)\right]}{\left(K\frac{d}{2}\right)J_0\left(K\frac{d}{2}\right)(R+pS)+2pL_0J_1\left(K\frac{d}{2}\right)}\cdot V1\cdot \tag{22}$$

The operational expression for the current given by (8) may now be changed using (20) and replacing $F(p)$ by (21) into

$$i=\frac{\left(K\frac{d}{2}\right)\cdot J_0\left(K\frac{d}{2}\right)}{\left(K\frac{d}{2}\right)J_0\left(K\frac{d}{2}\right)\cdot(R+pS)+2pL_0J_1\left(K\frac{d}{2}\right)}\cdot V1 \tag{23}$$

The total magnetic flux in the iron core as given by equation (2) now becomes

$$\Phi_i=\frac{L_0}{N}\cdot\frac{2J_1\left(K\frac{d}{2}\right)}{\left(K\frac{d}{2}\right)J_0\left(K\frac{d}{2}\right)\cdot(R+pS)+2pL_0J_1\left(K\frac{d}{2}\right)}\cdot V1 \tag{24}$$

4. Conversion of the Operational Solutions into Real Time Functions. Heaviside's unit function is known as the complex integral[9,3]

$$1=\frac{1}{2\pi j}\int_{-j\infty}^{+j\infty}\frac{\epsilon^{pt}}{p}\,dp, \tag{25}$$

where p means any variable in the complex plane. This time function is to be applied to the magnetic field strength given by equation (22). Introducing (22) in (25) gives the rather complicated complex integral

$$H_2=-\frac{N}{l'}\cdot\frac{V}{2\pi j}\cdot\int_{-j\infty}^{+j\infty}\frac{\left(K\frac{d}{2}\right)\cdot\left[J_0\left(K\frac{d}{2}\right)-J_0(Kr)\right]}{\left(K\frac{d}{2}\right)\cdot J_0\left(K\frac{d}{2}\right)(R+pS)+2pL_0J_1\left(K\frac{d}{2}\right)}\cdot\frac{\epsilon^{pt}}{p}\,dp\cdot \tag{26}$$

The evaluation of this integral depends on the integrand. We may prove that in this case the integrand is a rational function of p. Since the Bessel functions are generally given by the power series.[13,14]

$$\left.\begin{aligned}J_0(x)&=1-\frac{(x/2)^2}{1\,!^2}+\frac{(x/2)^4}{2\,!^2}-\frac{(x/2)^6}{3\,!^2}+-\dots\\J_1(x)&=\frac{x}{2}\cdot\left\{1-\frac{(x/2)^2}{1\,!\,2\,!}\right.\\&\qquad\left.+\frac{(x/2)^4}{2\,!\,3\,!}-\frac{(x/2)^6}{3\,!\,4\,!}+-\dots\right\}\end{aligned}\right\} \tag{27}$$

in which x, the argument, is identical with $\left(K\frac{d}{2}\right)$ in (26), it may be seen from that equation that $\sqrt{p}$ cancels throughout the fraction and that, therefore, the fraction is a rational function in terms of p.

In the case where the integrand of a complex integral is a rational function of the variable, it is permissible to replace the integral by the sum of the residues. This theorem in connection with the time function is known as Heaviside's expansion theorem.[9] So that, in other words, we may apply to the complex operational solutions, the general expansion theorem. It may be emphasized that this holds only in the case of rational functions in p.

For convenience replace the fraction in (26) by the symbolical expression

$$H_2=-\frac{N}{l'}\cdot\frac{V}{2\pi j}\int_{-j\infty}^{+j\infty}\frac{Y_2(p)}{Z(p)}\cdot\frac{\epsilon^{pt}}{p}\,dp$$

and readily obtain a solution in time functions as

$$H_2=-\frac{N}{l'}\cdot V\cdot\left\{\frac{Y_2(o)}{Z(o)}+\sum_{\nu=1}^{\infty}\left[\frac{Y_2(p)}{p\frac{d}{dp}Z(p)}\right]_{p=p_\nu}\cdot\epsilon^{p_\nu t}\right\} \tag{28}$$

whereby

$$Y_2(p)=\left(K\frac{d}{2}\right)\cdot\left[J_0\left(K\frac{d}{2}\right)-J_0(Kr)\right] \tag{29}$$

$$Z(p)=\left(K\frac{d}{2}\right)J_0\left(K\frac{d}{2}\right)\cdot(R+pS)+2J_1\left(K\frac{d}{2}\right)\cdot pL_0\cdot \tag{30}$$

Now the problem is to find the roots of the denominator function $Z(p)$.

In the case of the current we have again to prove that the integrand in (23) is a rational function in p. This also may be proved by means of equations (27). For convenience we introduce for the numerator function in (23) the symbolical expression

$$Y_i(p) = \left(K\frac{d}{2}\right)\cdot J_0\left(K\frac{d}{2}\right)\cdot \qquad (31)$$

The development according to the expansion theorem gives

$$i = V\left\{\frac{Y_i(o)}{Z(o)}\cdot + \sum_{\nu=1}^{\infty}\left[\frac{Y_i(p)}{p\frac{d}{dp}Z(p)}\right]_{p=p_\nu}\cdot\epsilon^{p_\nu t}\right\}. \qquad (32)$$

The total field flux is given by equation (24). Denoting the numerator function by

$$Y_\Phi(p) = 2J_1\left(K\frac{d}{2}\right), \qquad (33)$$

we can prove also in this case the integrand to be a rational function in p. In terms of the expansion theorem the expression for the total field flux becomes,

$$\Phi_t = \frac{L_0 V}{N}\cdot\left\{\frac{Y_\Phi(o)}{Z(o)} + \sum_{\nu=1}^{\infty}\left[\frac{Y_\Phi(p)}{p\frac{d}{dp}Z(p)}\right]_{p=p_\nu}\epsilon^{p_\nu t}\right\}. \qquad (34)$$

5. *General Discussion of the Results.* Now it becomes necessary to establish and check the time conditions of the problem. The eddy currents arise when switching on the electric circuit and they disappear under steady state conditions, because we have direct current. The steady state term is given in equation (28) by $\frac{Y_2(o)}{Z(o)}$ and must become zero. From the definition of K by equation (14), it is evident that $p = 0$ if $K = 0$. Introducing the latter values in the equations (29) and (30) gives after canceling $\left(K\frac{d}{2}\right)$

$$\frac{Y_2(o)}{Z(o)} = \frac{o}{R} = 0 \qquad (35)$$

The steady state terms of the magnetic field strength produced by the eddy currents are therefore zero.

The steady state value of the electric current i is given, since we have d-c. voltage, by

$$i_{t=\infty} = \frac{V}{R}\,. \qquad (36)$$

Since after canceling $\left(K\frac{d}{2}\right)$ equations (31) and (30) give

$$\frac{Y_i(o)}{Z(o)} = \frac{1}{R},$$

from which (36) checks as a result of (32).

Finally it is necessary to check the steady state term of the magnetic flux. Introducing $K = 0$ in (33) and (30), the steady state member in (34) becomes

$$\frac{Y_\Phi(o)}{Z(o)} = \frac{1}{R}, \qquad \Phi_{t=\infty} = \frac{L_0}{N}\cdot\frac{V}{R}, \qquad (37)$$

which value is found to be correct.

The dimension of p_ν must be 1/sec. because $p_\nu t$ as the exponent of the exponential function has the dimension 1. By observing these values we can determine the dimension of K. The argument of the Bessel function $\left(K\frac{d}{2}\right)$ must have the dimension 1. Since K is given by equation (14) we get for the root term the condition,

$$D\left(K\frac{d}{2}\right) = 1 = D\left(j\sqrt{\frac{l_s}{l'}\cdot\Lambda\,\Pi_0\frac{d^2}{4}}\cdot\sqrt{p}\right)\cdot$$

This means that the expression under the first root sign has the dimension of time which we may designate as θ and call the *magnetic time constant for the solid iron part.*

$$\theta = \frac{l_s}{l'}\cdot\Lambda\,\Pi_0\frac{d^2}{4}\ \text{sec.} \qquad (38)$$

This time constant will be of great importance in the following considerations. Its physical meaning is similar to the *electric time constant* given by

$$T_1 = \frac{L_1}{R}, \qquad (39)$$

where L_1 designates the total inductance of the electric current from the relation

$$L_1 = L_0 + S. \qquad (40)$$

As mentioned before, S indicates the leakage inductance and L_0 the inductance of the magnetic flux in the iron core only. Therefore the electric time constant may be decomposed into

$$T_1 = \frac{L_0}{R} + \frac{S}{R} = T_0 + T_s\,. \qquad (41)$$

T_0 may be called the *fictitious magnetic time constant,* holding in that case where the current and its field have the same shape, no leakage being present.

The roots p_ν must have negative and real values, therefore, for convenience we may define a new quantity by

$$\theta\,p_\nu = -\,q_\nu^2\,. \qquad (42)$$

The argument of the Bessel functions takes the real values

$$j\sqrt{\theta\,p_\nu} = +\,q_\nu = K\frac{d}{2} \qquad (43)$$

It is useful to change the expressions for the magnetic field and the current into functions of this new variable q. First introduce q in the numerator functions getting

$$\left.\begin{aligned} Y_2\,(q) &= +q\,.\left[J_0\,(q) - J_0\left(q\,\frac{2\,r}{d}\right)\right] \\ Y_i\,(q) &= +q\,.\,J_0\,(q) \\ Y_\Phi\,(q) &= +2\,.\,J_1\,(q) \end{aligned}\right\} \tag{44}$$

The general denominator function $Z\,(p)$ may be changed into

$$Z\,(q) = q\,.\,J_0\,(q)\left(R - \frac{q^2}{\theta}\,S\right) - 2\,J_1\,(q)\cdot\frac{q^2}{\theta}\,L_0\,.$$

Taking $q\,\dfrac{L_0}{\theta}$ as a constant factor gives

$$Z\,(q) = q\,\frac{L_0}{\theta}\cdot\left[J_0\,(q)\cdot\frac{\theta}{T_0} - q^2\cdot\frac{S}{L_0}\cdot J_0\,(q) - 2\,q\,J_1\,(q)\right]. \tag{45}$$

Here we may introduce for the factor

$$\frac{S}{L_0} = \sigma\,. \tag{46}$$

The symbol σ is called the "leakage coefficient" as it is used in the design of electrical machinery and transformers. It is the ratio of leakage flux to useful flux. Rearranging (45) gives the final expression

$$Z\,(q) = q\,\frac{L_0}{\theta}\left[J_0\,(q)\left(\frac{\theta}{T_0} - q^2\,\sigma\right) - J_1\,(q)\,.\,2\,q\right]. \tag{47}$$

Putting $Z\,(q)$, as given in equation (47), equal to zero we have the *transcendental equation for the roots*

$$\frac{J_0\,(q)}{J_1\,(q)} = \frac{2\,q}{\dfrac{\theta}{T_0} - \sigma\,q^2} \tag{48}$$

The solution of this equation (48) will be given in the next part. But we can see already the importance of the so-called *relative time constant* $\dfrac{\theta}{T_0}$.

It is also necessary to transform $p\,\dfrac{d}{d\,p}\,Z\,(p)$ into a function of q. Introducing (42) and (43) in the derivative of the general function $Z\,(q)$ (30) and with some simplification we obtain

$$\left[p\,\frac{d}{d\,p}\,Z\,(p)\right] = \frac{1}{2}\,q\,\frac{L_0}{\theta}\cdot\left\{J_0\,(q)\cdot\left[\frac{\theta}{T_0} - q^2\,(3\,\sigma + 2)\right] - q\,J_1\,(q)\left[\frac{\theta}{T_0} - (q^2\,\sigma - 2)\right]\right\}. \tag{49}$$

The final expressions for the magnetic field strength H_2, the current i and the total flux in the iron core Φ_i are now to be found as

$$H_2 = -\,2\,\frac{\theta}{T_0}\cdot\frac{N}{l'}\cdot\frac{V}{R}\cdot\sum_{\nu=1}^{\infty}\left[\frac{J_0\,(q) - J_0\left(q\,\dfrac{2\,r}{d}\right)}{J_0\,(q)\left[\dfrac{\theta}{T_0} - q^2\,(3\,\sigma + 2)\right] - q\,J_1\,(q)\left[\dfrac{\theta}{T_0} - (q^2\,\sigma - 2)\right]}\right]_{q=q_\nu} \epsilon^{-q_\nu^2\frac{t}{\theta}} \tag{50}$$

$$i = \frac{V}{R}\cdot\left\{1 + 2\,\frac{\theta}{T_0}\cdot\sum_{\nu=1}^{\infty}\left[\frac{J_0\,(q)}{J_0\,(q)\left[\dfrac{\theta}{T_0} - q^2\,(3\,\sigma + 2)\right] - q\,J_1\,(q)\,.\left[\dfrac{\theta}{T_0} - (q^2\,\sigma - 2)\right]}\right]_{q=q_\nu} \epsilon^{-q_\nu^2\frac{t}{\theta}}\right\} \tag{51}$$

$$\Phi_i = \frac{V\,T_0}{N}\cdot\left\{1 + 4\,\frac{\theta}{T_0}\cdot\sum_{\nu=1}^{\infty}\left[\frac{\dfrac{1}{q}\cdot J_1\,(q)}{J_0\,(q)\left[\dfrac{\theta}{T_0} - q^2\,(3\,\sigma + 2)\right] - q\,J_1\,(q)\left[\dfrac{\theta}{T_0} - (q^2\,\sigma - 2)\right]}\right]_{q=q_\nu} \epsilon^{-q_\nu^2\frac{t}{\theta}}\right\}, \tag{52}$$

III. Practical Use of the Theory and Discussion

1. Determination of the Roots of Z (q). Before applying the above equations to special problems it becomes necessary to determine the roots of $Z(q)$. The fundamental equation for the roots is given by

$$\frac{J_0(q)}{J_1(q)} = \frac{2q}{\dfrac{\theta}{T_0} - \sigma q^2}. \tag{48}$$

The unknown quantities in this expression are σ and $\dfrac{\theta}{T_0}$. The leakage coefficient σ may be assumed to have the value 0.25 as is commonly found in electrical machinery. Introducing this numerical value the roots q_ν become functions only in $\dfrac{\theta}{T_0}$, which will appear as a determining parameter.

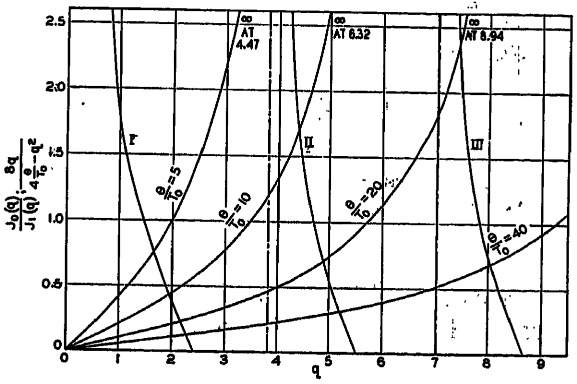

Fig. 3—The Determination of the Roots of $Z(q)$

The solution of the highly transcendental equation (48) can be given either graphically or by approximate calculation. To obtain the results more precisely we shall combine these two methods. To obtain a graphical solution as a first approximation plot curves for the left hand side and the right hand side of equation (48), and locate the intersections of these two families of curves. In Fig. 3 is shown the family of curves $\dfrac{J_0(q)}{J_1(q)}$, the left hand member of (48) which are similar to the function tan q having a variable frequency. The curves of the right hand side have involved the parameter $\dfrac{\theta}{T_0}$ for which the numerical values 5, 10, 20, and 40 have been arbitrarily chosen. From Fig. 3 the abscissas of the intersecting points may be taken as a first approximation and their numerical values may be checked by calculation of the ordinates. Table I shows such calculated results. For more detailed explanations see the mathematical Appendix 1.

TABLE I—THE FIRST 6 ROOTS OF $Z(q)$

$\theta/T_0 =$	5	10	20	40
$q_1 =$	1.645	1.955	2.168	2.285
$q_2 =$	3.964	4.400	4.900	5.20
$q_3 =$	6.60	6.885	7.435	8.05
$q_4 =$	9.45	9.594	9.94	10.65
$q_5 =$	12.38	12.44	12.66	13.19
$q_6 =$	15.42	15.47	15.56	15.77

2. The Curves of the Magnetic Field and of the Current. The final expressions for the current and for the total flux in the iron core are given by (51) and (52). They may be written symbolically:

$$\frac{i}{i_\infty} = 1 + \sum_{\nu=1}^{\infty} I_\nu \cdot \epsilon^{-\left(q_\nu^2 \frac{T_0}{\theta}\right)\cdot\frac{t}{T_0}}, \tag{54}$$

$$\frac{\Phi_i}{\Phi_{i\infty}} = 1 + \sum_{\nu=1}^{\infty} F_\nu \cdot \epsilon^{-\left(q_\nu^2 \frac{T_0}{\theta}\right)\cdot\frac{t}{T_0}}, \tag{55}$$

in which the steady state values of current and field have been designated by i_∞ and $\Phi_{i\infty}$, respectively, and the exponents have been changed by the introduction of T_0 to maintain the form of the parameter $\dfrac{\theta}{T_0}$ as follows:

$$-\frac{q_\nu^2}{\theta}\,t = -\left(q_\nu^2 \cdot \frac{T_0}{\theta}\right)\cdot\frac{t}{T_0}. \tag{53}$$

The time scale is changed into a relative time scale $\dfrac{t}{T_0}$, as seen from (53). The expressions (54) and (55) in the given form can be readily compared with the solution in the case where no eddy currents are present:

$$\frac{i}{i_\infty} = 1 - \epsilon^{-\frac{t}{T_1}}.$$

The single term in this last expression has to be replaced by the sum in (54) and (55). From Table II and III the values of the harmonic amplitudes I_ν and F_ν may be taken as functions of $\dfrac{\theta}{T_0}$. The amplitudes of higher order become positive according to the fact that the total sum must be equal to minus one.

To get the magnetic field and the current as time functions, the amplitudes as shown in Tables II and III are to be multiplied by the exponential time-functions. The results may be seen in Fig. 5. For detailed explanation see the mathematical Appendix 2. As $\dfrac{\theta}{T_0}$ increases, the curves of the magnetic field have decreasing values for each abscissa, considering distinct values of the relative time scale $\dfrac{t}{T_0}$. The time

TABLE II—THE FIRST SIX HARMONIC AMPLITUDES I_ν OF THE CURRENT

θ/T_0 =	5	10	20	40
I_1	−0.619	−0.395	−0.218	−0.116
I_2	−0.268	−0.324	−0.244	−0.132
I_3	−0.079	−0.169	−0.252	−0.177
I_4	−0.027	−0.063	−0.155	−0.232
I_5	−0.010	−0.025	−0.065	−0.189
I_6		−0.011	−0.028	−0.092
Total	−1.003	−0.987	−0.962	−0.938

TABLE III—THE FIRST THREE HARMONIC AMPLITUDES F_ν OF THE MAGNETIC FIELD

	5	10	20	40
F_1	−1.000	−0.931	−0.85	−0.790
F_2		−0.087	−0.15	−0.158
F_3				−0.066
Total	−1.000	−1.018	−1.00	−1.014

constant of this family of curves must be a function of the ratio $\dfrac{\theta}{T_0}$. The curves of the current show a high rate of increase at low values of the time scale but they tend toward definite constants at very high values of the time scale.

3. The Time Constant of the Magnetic Field. From Table III it will be noted that the first harmonic of the magnetic field has very high values compared with the harmonics of higher orders. Therefore, the value of the time function is determined generally by the time constant of the first harmonic. This time constant is given by

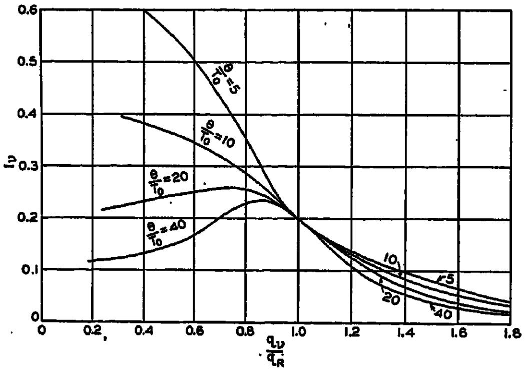

FIG. 4—THE HARMONIC AMPLITUDES OF THE CURRENT AS FUNCTIONS OF THE ROOTS

$$T_\Phi = T_0 \cdot \left(\frac{\theta}{T_0} \Big/ q_1^2 \right) \qquad (56)$$

and for convenience this expression may be changed into

$$T_\Phi = F \cdot T_1 = \left(\frac{T_0}{T_1} \cdot \frac{\theta}{T_0} \Big/ q_1^2 \right) \cdot T_1 \qquad (57)$$

The ratio $\dfrac{T_0}{T_1}$ equals $\dfrac{1}{1+\sigma}$ as may be seen from equation (7). The factor F is now a function of $\dfrac{\theta}{T_1}$. The calculation gives the curve in Fig. 6 which shows its asymptotic character. The straight line to which this curve approaches is given by the first root of the Bessel function of zero order, which value[13] is 2.4048.

At $\dfrac{\theta}{T_1} = 0$ the curve of F approaches unity which means that if the solid iron part of the magnetic circuit is considered to disappear the time constant of the magnetic field will become identical with the time constant of the exciting current. The *presence of eddy currents increases* the time constant of the magnetic field.

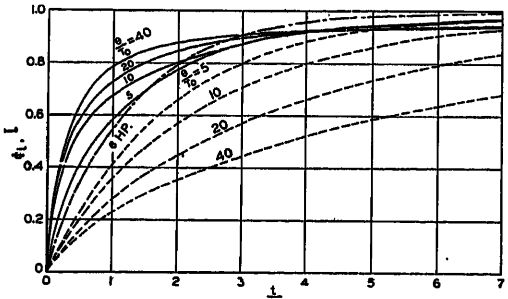

FIG. 5—THE CURVES OF FIELD (- - - -) AND CURRENT (———) AS FUNCTIONS OF THE RELATIVE TIME t/T_0 COMPARED WITH THE EXPONENTIAL FUNCTION (— – —)

For practical purposes the function F may be replaced very closely by two straight lines intersecting one another at $\dfrac{\theta}{T_1} = 5$. The best approximation is given by

$$F = K_1 + K_2 \frac{\theta}{T_1}, \quad K_1 = 1 \quad, K_2 = 0.12 \text{ if } \frac{\theta}{T_1} \leqq 5,$$

$$K_1 = 0.75, K_2 = 0.175 \text{ if } \frac{\theta}{T_1} \geqq 5. \qquad (58)$$

Introducing these values in (57) the time constant of the magnetic field takes the very simple form

$$T_\Phi = T_1 + 0.12\,\theta \qquad \text{if } \frac{\theta}{T_1} \leqq 5,$$

$$T_\Phi = 0.75\,T_1 + 0.175\,\theta \text{ if } \frac{\theta}{T_1} \geqq 5. \qquad (59)$$

The total time constant T_Φ is composed of T_1, the time constant of the electric circuit, and a fraction of θ, the time constant of the solid iron part. There is *no addition* of these time constants but only a composition of their fractional values. This is one of *the most important results* in this paper.

The definition for θ is given by equation (38). This relation may be simplified if Π_0 is replaced by its numerical value $4\pi \cdot 10^{-9}$ and writing in place of $\frac{\pi d^2}{4}$, the area A of the cross-section of the iron core. Although the derivation is based on the assumption of circular cross-section, the results may be used in all cases where the cross-section is approximately circular. Introducing this statement, θ becomes

$$\theta = 0.4\, \gamma \cdot A \frac{\lambda_s}{\lambda_s + \frac{1}{\mu}} \cdot 10^{-4} \text{ sec.} \qquad (60)$$

The electric time constant was given as

$$T_1 = \frac{L_1}{R} = \frac{(1+\sigma)\, L_0}{R}\, . \qquad (61)$$

It is easy to see that θ depends upon the dimensions of the solid iron part, that is, the area of its cross-section and its length. In the same manner the conductivity and the permeability are influencing factors. The electric time constant on the contrary depends merely on the parameters of the electric circuit, as inductance and resistance.

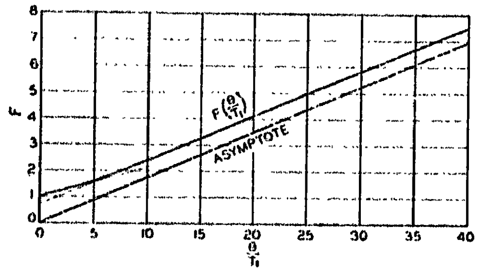

FIG. 6—THE TIME CONSTANT OF THE MAGNETIC FIELD $T_\phi = F\, T_1$

4. The Equivalent Self-Inductance for the Eddy Currents. The magnetic time constant as given by (57) may be written in the form of the electric time constant

$$T_\Phi = \frac{L_\Phi}{R},$$

in which L_Φ indicates any fictitious self-inductance with respect to the field. Taking from (57) the expression T_Φ and replacing T_1 by (61) we get the identity

$$L_\Phi = F \cdot L_1 \cdot$$

Subtracting the total inductance, the remainder must be produced by the eddy currents. It may be called the *"equivalent self-inductance" for the eddy currents.* and the expression for it becomes,

$$L_0 = (F - 1) \cdot L_1 \cdot \qquad (62)$$

The physical meaning of (62) is that of an additional self-inductance, whenever magnetic circuits, containing a solid iron part, are considered with respect to a switching phenomenon. It may be emphasized that this increase of self-inductance holds only for the magnetic field. The electric current, however, shows, as may be seen from Fig. 5, a large decrease of the time constant, but the shape of the current curve cannot be expressed as a simple exponential function. The assumption of a representative time constant has no physical sense in the case of the current.

5. Numerical Example. To get a conception of the numerical value of the physical quantities, involved in this problem, a simple numerical example may be considered. The magnetic circuit may be given by a torroidal iron core as assumed in Section 3 and shown in Fig. 1. The lengths of the different parts of the iron path may be

$$l = 250 \text{ cm.}, \quad \delta = 2.5 \text{ cm.}, \quad l_s = 100 \text{ cm.}$$

and the diameter of the cross-section be $d = 30$ cm. The material of the solid iron part as well as of the laminated iron part may be cast steel with the material constants

$$\gamma = 8 \text{ Mho } m/m\, m^2, \quad \mu = 1000.$$

The electric circuit is characterized by the inductance $L_0 = 12.77\, H$, the leakage coeffiicent $\sigma = 0.25$ and the resistance $R = 5.72$ ohm.

The magnetic time constant of the solid iron part is, according to (60),

$$\theta = 0.4 \cdot 8 \cdot \frac{30^2\, \pi}{4} \cdot \frac{0.4}{0.01 + 0.001}\, 10^{-4} = 8.18 \text{ sec.}$$

The electric time constant is, according to (61),

$$T_1 = \frac{12.77. + .25}{5.72} = 2.8 \text{ sec.}$$

The ratio $\frac{\theta}{T_1}$ is 2.93, which being less than 5 dictates the use of the first values in equation (59). The total magnetic time constant becomes, therefore

$$T_\Phi = 2.8 + 0.12 \,.\, 8.18 = 3.80 \text{ sec.}$$

The electric time (current) must be increased by 36 per cent to give the magnetic time constant. Arithmetic addition would have given nearly three times this value. Consequently the importance of having an accurate formula for the magnetic time constant due to eddy current effects is made clear.

The variation of the time constant T_Φ with the length of the solid iron part is shown in Fig. 7. It is assumed there that the electric time constant T_1 has two different values, one for each of two different exciting coils without change of the iron core. From these two curves the influence of θ relative to the electric time constant is made clear. In the case $T_1 = 2.8$ sec., the range of T_Φ is from 1 to 2 but in the case $T_1 = 1$ sec., the range of T_Φ becomes 1 to 4.33.

To lower the magnetic time constant in the case of solid iron in any magnetic circuit, it is necessary to change the dimensions of the solid iron part *as well as* to change the parameters of the electric circuit. It depends on the ratio of the electric to the magnetic time constant which change will be more effective. This can be decided by calculation according to formulas (**60**) and (**61**).

IV. Application to Switching Problems in Synchronous and D-C. Machines

1. *Quick Response Excitation of Large A-C. Generators.* In order to improve the system stability under short-circuit conditions of short duration it has been found advantageous to increase suddenly the excitation power input.[15,16] A measure of the effectiveness of this method is thought to be the rate of change of voltage at the terminals of the main exciter machine in volts per second. The rate of change in the magnetic field of the generator is obviously much less than the rate of change in the quick response excitation voltage. The greater the rate of change of the exciting current the greater the rate of change of the eddy currents in the solid iron part of the magnetic circuit of the generator.

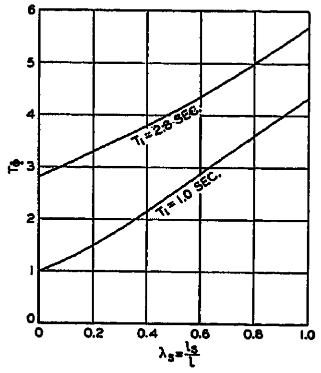

Fig. 7—The Magnetic Time Constant as Function of the Relative Length of Solid Iron Core in a Special Case

The theory treated in this paper gives a solution in the case of a d-c. voltage suddenly impressed upon an electromagnetic system, such as a synchronous machine. In the synchronous machine as in the torroidal core, there is a magnetic circuit partly laminated and partly solid. The high rate of increase in the excitation voltage may with close approximation be replaced by a suddenly impressed d-c. voltage, which value is that of the maximum exciter voltage. In the case of an alternator the stator winding introduces a difference in the theory thus far considered. Further investigation on this subject may take into account the two electric circuits that is, the field and stator circuits. For first approximation only the effect of the impressed excitation voltage will be considered. The opposing induced eddy currents produce a time lag of the magnetic field, the time constant of which is given by equation (**59**). This time constant must be made a minimum in order to have the best effect in producing a quick response excitation. Even the highest increase of voltage in the exciting circuit cannot be successful with respect to the system stability when the time constant of the magnetic circuit is too large. The effect lies in the rate of change of the magnetic field rather than in the rate of change of the exciting voltage. Equation (**59**) shows the most economic way to increase the effectiveness of the super-excitation of an alternator without using larger exciters. On the other hand it is known that the synchronizing torque of an alternator is decreased when all parts of the magnetic circuit are laminated. The asynchronous eddy currents due to the oscillations of the pole system with respect to the system voltage vector increase the synchronizing power.

It is seen, therefore, that there are two opposing conditions in regard to the proportions of laminated and solid iron parts, and the best proportion may be stated in terms of the amount of solid iron to be used in an alternator to restrict the magnetic time constant to a given limit. The time range in which the effect of super-excitation shall have become established is about 0.2 to 0.6 seconds according to the kind of short circuit. The magnetic time constant T_Φ must be at least within this range, so it may be taken as an average value of 0.4 seconds. The application to other values is easily accomplished. It may be assumed that the electric time constant T_1 is one-half of the total magnetic time constant, which means the very low value of 0.2 second. Then from (**57**)

$$T_\Phi = F \, . \, T_1 \, ,$$

in which

$$F = 2.$$

Fig. 6 shows as abscissas the value

$$\frac{\theta}{T_1} = 8, \text{ or } \theta = 8 \, T_1 = 1.6 \text{ sec.}$$

The equivalent time constant for the solid iron part, θ, is given by (**60**) and here expressed in the form

$$\theta = 0.4 \, \gamma \frac{A \, . \, l_s}{\delta + \dfrac{l}{\mu}} \cdot 10^{-4} \text{ sec.} \qquad (63)$$

In the case of the alternator it is useful to introduce $A \, l_s$ as the volume of the solid iron part. When different parts with different dimensions are in series the total sum is to be taken. This is permissible only in accordance with the proportionality of θ to the volume, as expressed in (**63**) and furthermore with the proportionality of T_Φ to θ, as shown in equation (**59**). If there were several air-gaps, also the sum of their lengths must be entered in (**63**).

The relative permeability μ, as a physical quantity, may be usefully replaced by an expression in ampere-turns, in order to simplify the application in electrical engineering mathematics. Equation (**3a**) which stated that the line integral of the magnetic field strength H_1 was identical with the sum of the ampere-turns for the different paths, gives the definition for μ as,

$$\delta \, H_1 + \frac{l - \delta}{\mu} H_1 = N i$$

$$A \, T \text{ (air-gap)} + A \, T \text{ (iron)} = A \, T \text{ (total).}$$

So it may be written

$$\frac{l}{\mu} = l\,\frac{N\,i - \delta\,H_1}{(l-\delta)\,H_1}$$

$$= \frac{l\,\delta}{l-\delta} \cdot \frac{A\ T\ (\text{total}) - A\ T\ (\text{air-gap})}{A\ T\ (\text{air-gap})} \cdot \quad (64)$$

In this definition all the quantities are well known both in the theory and in the design of electrical machines. Finally the conductivity γ may be replaced by the numerical value for cast steel, because in alternators cast steel is generally used for the solid iron part, $\gamma = 8$ Mho $m/m\,m^2$. From (63) it follows, that large values of the air-gap δ, and large values of $\frac{l}{\mu}$, the length of a fictitious air-gap equivalent to the iron path, which means low values of permeability for whatever kinds of iron are used, are both desirable. Similarly low values of conductivity of the iron and a small volume of solid iron are advantageous.

To continue the numerical example, the magnetic circuit in the case of an alternator is formed by two poles, the connecting yoke, two air-gaps, and the path through the stator.

Let $\delta = 2 \cdot 2 = 4$ cm., $l = 350$ cm.,
$A\ T$ (total) $= 40{,}000\ A$, $A\ T$ (air-gap) $= 30{,}000\ A$.
According to (64) it will be found that

$$\frac{l}{\mu} = \frac{350 \cdot 4}{346} \cdot \frac{40{,}000 - 30{,}000}{30{,}000} = 1.35 \text{ cm.}$$

and therefore

$$\theta = 0.4 \cdot 8 \cdot \frac{\Sigma\ (F\ .\ l_s)}{4 + 1.35} \cdot 10^{-4} = 0.6.\ \Sigma\ (F\ l_s)\ .\ 10^{-4} \text{ sec.}$$

whereby the summation is taken over the entire solid iron parts in the magnetic circuit. Substituting in this expression the numerical value 1.6 seconds, the condition is found for the volume of the solid iron as

$$\Sigma\ (F \cdot l_s) \leqq \frac{1.6}{0.6} \cdot 10^4 = 2.67\ .\ 10^4 \text{ cm.}^3$$

This is the criterion for the amount of solid iron in the magnetic circuit to maintain the total magnetic time constant below or about 0.4 seconds.

In each case such a criterion may be easily derived. But a general expression for it cannot be given because of the transcendental character of the factor F. To use the approximation (59), first $\frac{\theta}{T_1}$ must be known, but the value of this ratio can be determined only at the end of the computation, so, therefore, it might be necessary to repeat the entire procedure. Only the following condition of the total volume of solid iron, as dependent on the magnetic time constant θ, may be generalized in the form

$$\Sigma\ (F \cdot l_s) \leqq \frac{\delta + \frac{l}{\mu}}{3.2} \cdot 10^4 \cdot \theta_c \text{ cm.}^3 \quad (65)$$

where θ_c means the critical value of θ in the special case as considered above.

Generally it is noticed that a continuous increase of voltage instead of a suddenly impressed voltage, as assumed in this paper, would increase somewhat the final magnetic time constant. But this influence is neither so important nor large that it should change the theory developed in this paper.

The effect of saturation could be introduced by composing the final solution of a sum of partial solutions each holding for a range of the magnetizing curve in which it may be considered as an approximate straight line. The suggestion of a standard magnetizing curve[17, 18] might be of great value in applying this method of getting a general solution. But this method would be very laborious. Therefore, the results given in this paper may be taken as a first and apparently very important approximation to the final solution.

2. *Other Fields of Application.* A very important field of application may be found in all magneto-electric systems where regulation is influenced by the magnetic inertia.

The large d-c. motors in reversing rolling mills have a limitation imposed upon the succession of their different processes by the magnetic time constant of a solid iron yoke. In critical cases it is of importance to know with more precision the real magnetic time constant of a solid iron part as a member in the magnetic circuit. It is especially important in cases where the speed of production should be increased to know the possibilities of existing motors and to know what changes should be made when the time constant is too large.

One of the most important fields of application, however, is in the computation of the short-circuit currents in large generators. Such calculations are highly inaccurate as evidenced by the permissible international tolerances of ± 30 per cent in the peak value.[19] Such values are most unsatisfactory when compared with the relatively high precision of other electrical calculations, and it is hoped that refined methods in short-circuit calculations may be prepared in an additional paper using as a basis the method suggested in this treatise.

ACKNOWLEDGMENT

The author wishes to acknowledge with appreciation the aid of Professor Robin Beach who so kindly improved the English presentation.

Mathematical Appendix

1. To obtain the curves in Fig. 3 showing the ratio $\frac{J_0\ (q)}{J_1\ (q)}$ the tables of E. Jahnke-F. Emde[13] and Gray and Mathews[14] are used. For simplification the values of the roots of the Bessel functions $J_0\ (q) = 0$ and $J_1\ (q)$

$= 0$ are marked by making the ratio $\frac{J_0(q)}{J_1(q)}$ equal to zero and infinity, respectively. So we get the intersections with the axis of abscissas and the asymptotic straight lines. The slope of the curves in their intersections with the axis of abscissas is given by

$$\frac{d}{dq}\left(\frac{J_0(q)}{J_1(q)}\right) = \frac{-J_1^2(q) - J_0^2(q) + \frac{1}{q} J_1(q) J_0(q)}{J_1^2(q)},$$

and introducing the value $J_0(q) = 0$ we get the simple numerical value

$$\frac{d}{dq}\left(\frac{J_0(q)}{J_1(q)}\right)\Big/_{J_0=0} = -1.$$

2. To prove the calculation of the harmonic amplitudes of the field and of the current, we plot these amplitudes against the roots of the denominator function $Z(q)$. For simplification a so-called "resonance-root" of this function may be introduced. Placing the denominator of the right hand member in equation (48) with $\sigma = 0.25$ equal to zero, we obtain the definition

$$4\frac{\theta}{T_0} = q_R^2, \quad q_R = 2\sqrt{\frac{\theta}{T_0}}.$$

Taking instead of the roots q_ν themselves, the ratio of the roots to this resonance root q_R as abscissas, we get the curves in Fig. 4 in the case of the current. The value for the fictitious harmonic amplitude at $q = q_R$ may be taken from (**51**), as after introducing $J_1 = 0$ in order to make $\frac{J_0(q)}{J_1(q)} = \infty$,

$$I(q_R) = 2\frac{\theta}{T_0} \cdot \frac{1}{\frac{\theta}{T_0} - 275\, q_R^2}.$$

Introducing q_R according to the definition, this expression becomes

$$I'(q_R) = -0.2.$$

All curves must, therefore, intersect the axis of ordinates at a value -0.2. This is seen to be true from an inspection of Fig. 4.

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Discussion

H. Poritsky: The author is to be congratulated upon his successful treatment of an important subject for which no adequate solution has thus far been offered. The example chosen, while highly idealizing the actual structure of a generator, yet illustrates all the essential features of the problem, and the treatment by means of Heaviside's Operational Calculus, leaves nothing to be desired.

The reviewer wonders, however, whether an equally illustrative yet simpler example could not even further simplify the problem. Thus, if in place of an iron core a yoke is used such as shown in Fig. 1, with width *w* considerably larger than the thickness *t*, we obtain a case resulting in a *one-dimensional* problem in the heat equation. The Bessel functions then would be eliminated in favor of hyperbolic or circular functions.

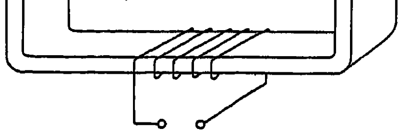

FIG. 1

Again, the case of a long, solid, cylindrical rotor, placed in a laminated stator, has been briefly examined by the reviewer. This case allows direct treatment along similar lines, with no added complexity, yet approximates even better to the actual case of a turbo alternator.

Interconnection Services

Their Classification and Evaluation

BY ALEX. E. BAUHAN*

Member, A. I. E. E.

Synopsis.—*The services rendered by an interconnection between two or more electric power systems may be classified as:*

1. Emergency service—by which assistance is given by one system to the other in event of breakdown of equipment or other abnormal conditions.

2. Load diversity—arising from the non-coincidence of the times of peak loads in the interconnected systems.

3. Firm power—transactions involving a definite advance commitment by one company to sell power and energy to the other for use in lieu of installed capacity.

4. Storage power—by which off-peak energy from one system is converted into peak capacity in the other through the medium of storage.

5. Intra-company use—referring to the use of interconnecting facilities for the internal purposes of one of the parties.

6. Economy flow—by which generation in one system is replaced by more economical generation in the other system; and

7. Unintentional flow.

The foregoing services may be evaluated, as far as capital cost is concerned, by determining the aggregate saving in generating capacity and multiplying by the estimated cost per kilowatt of generating capacity and then comparing the result with the capital cost of the interconnection.

The more important annual-cost comparison is made by:

1. Determining the difference between the fixed charges on the avoided generating station investment and the fixed charges, including operation and maintenance, on the interconnecting facilities.

2. Determining the saving in fixed element of production expense arising from the avoided capacity.

3. Determining the change in the variable element of production expense due to interconnection.

THE word *interconnection* as used in this paper refers to the physical tying together of two or more independently owned or managed electric systems for the purpose of realizing financial benefits or improvement of service by the interchange of power and energy. The subject of interconnection may be considered under the following divisions:

1. Classification of Services
2. Evaluation, Economics
3. Contract
4. Design and Construction
5. Operation

of which this paper deals only with the first two.

I—CLASSIFICATION OF SERVICES

The determination of the economic merits of an interconnection, its evaluation, is much facilitated by an orderly and logical classification of the services which that interconnection will render. Recognition of the various classes of service is not only helpful but is quite essential in the preparation and application of the interconnection contract, as each class of service requires different provisions and rates of payment. Such classification is helpful in rationalizing design,—for instance in determining whether the services to be rendered by the interconnection warrant a double circuit or only a single circuit. The various services are of course the substance of operation.

What is offered here is not intended to be an enumeration of the benefits rendered by interconnection but rather a delineation of types of transactions which take place over interconnections. It is an attempt at earmarking or labelling the various amounts of power or blocks of energy in the light of what they do, of what service they perform, as necessitated principally by evaluation and contractual expression. The classification is submitted with the thought that it may form the basis of discussion and trial which will eventually bring out a generally acceptable classification and nomenclature. It recognizes the following seven main service divisions:

1. Emergency service
2. Load diversity
3. Firm power
4. Storage power
5. Intra-company use
6. Economy flow
7. Unintentional flow

1. Emergency Service

By emergency service is meant the assistance which one of the interconnected companies renders to the other on account of breakdown of equipment, unusual load demands, or other abnormal conditions resulting in need for power in excess of the capacity available from the normal power sources of the company in difficulty.

For the purposes of evaluation, and possibly for contractual reasons, it may be necessary to distinguish between *system emergency service* and *transmission emergency service.* The former has to do, in a well-consolidated system, with conditions of load and generating capacity in the whole system. It is associated with the more substantial ties between important centers of the systems. Sometimes when this service makes possible a definite recognizable reduction in the

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*Interconnection Engineer, Public Service Electric and Gas Co., Newark, N. J.

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amount of reserve generating capacity it is referred to as *reserve diversity*. Transmission emergency service on the other hand is concerned with small interconnections between the fringes of neighboring systems. Such service reinforces the normal transmission, which perhaps consists of only a single circuit, to a particular outlying part of one or both systems. Of course each type of emergency service brings with it something of the other and in some interconnections both are of importance.

Another class of emergency service arises from transactions which involve the transmission of emergency service from or to a third party or between a third and fourth party through the interconnection of the two parties under consideration. This classification need be recognized only if such flow be accorded contractual treatment different than that given to emergency transactions between the two parties immediately at interest.

The energy associated with emergency service is commonly looked upon as being simply that necessitated by the emergency, the flow being limited to the extent and duration of the need for outside assistance.

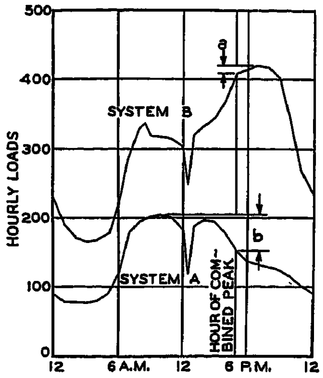

FIG. 1—DAILY DIVERSITY = $a + b$

2. *Load Diversity*

Load diversity refers to those transactions which result in a saving of generating capacity by reason of the non-coincidence of the times of the peak loads of the interconnected companies.

For instance, if a system having a morning peak and a relatively light load in the late afternoon is interconnected with a system having its peak at five o'clock in the evening and considerably less load in the morning, a saving in required generating capacity results. This saving in generating capacity, which is spoken of as the diversity, is equal to the sum of the individual peak loads minus the peak load of the combined systems. If the diversity is found to be say 40,000 kw. and is equally divided between the two companies, each at the time of its peak could receive 20,000 kw. from the other and thus realize a saving of installed generating capacity of that amount. The power and energy blocks flowing over the interconnecting lines as a result of this transaction are spoken of as diversity power and diversity energy.

It is not necessary that the load-diversity energy be considered to flow equally in opposite directions, as in the foregoing case. As a matter of agreement the flow can be divided in any other way. In event one of the companies is not in a position to curtail its installed generating capacity by reason of already having a surplus, all the capacity saving might be taken by the other company. This means that all of the diversity power would flow in one direction and instead of being returned in kind, could be adjusted by a money payment. Such a transaction and the flow resulting might, however, be considered to be equally divided and equally exchanged load diversity, with a one-way firm-power sale in the amount of one-half of the diversity saving superimposed on it.

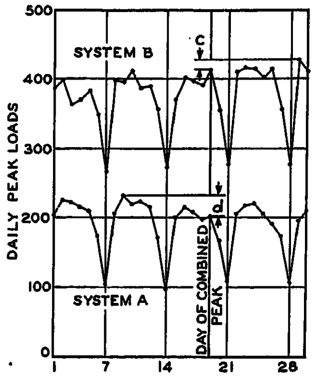

FIG. 2—MONTHLY DIVERSITY = $c + d$

Daily, Monthly, and Yearly Diversities. As an aid in determining diversity and later in laying out operating schedules for its realization it is sometimes advisable to subdivide diversity into daily diversity, monthly diversity, and yearly diversity.

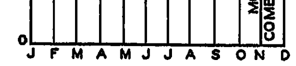

FIG. 3—YEARLY DIVERSITY = $e + f$

Daily load diversity is the diversity which occurs within any particular day. Monthly diversity is the diversity as among the daily peak loads of any particular month. Yearly diversity is the diversity as among the monthly peak loads in any particular year. Figs. 1, 2, and 3 illustrate respectively these three classes of diversity.

Note that in these illustrations the diversity is determined as being the sum of the differences for each system of its peak load and its load at the time of combined peak. This is somewhat different than the common expression for diversity, *viz.*, "the sum of the individual system peaks minus the peak of the combined systems;" but it is the mathematical equivalent. The form used in the illustrations will be found far more convenient in thinking of and working with diversity problems, particularly in cases where the combined peak occurs simultaneously with the peak of one of the systems. When this is the case, and it usually is when one of the systems is appreciably larger than the other, the diversity is determined independently of the system whose peak is simultaneous with the combined peak and is equal simply to the difference between the other's peak load and its load at the time of the combined peak.

Installed-Capacity versus Operated-Capacity Reductions. Our interest in load diversity arises mainly in the reduction in installed generating capacity which it makes possible. This reduction of installed generating capacity is equal to the daily diversity of the combined-peak day plus the monthly diversity of the combined-peak month plus the yearly diversity. There may in the non-peak periods of the year be monthly and daily diversities which effect no saving in the installed generating capacity. These can, however, be taken advantage of to reduce the amount of capacity operated. The parties to an interconnection may therefore wish to distinguish between load-diversity service reducing installed capacity and that reducing operating capacity. Diversity which only reduces the operating capacity is of relatively small importance. In fact, it is better not to consider this service as being diversity. It really comes under the category of "economy flow,"—discussed in detail later.

Scheduled Diversity and Call Diversity. Another classification of load diversity, one which is called for only by contractual and operating convenience, and then only in highly refined operations, is that which divides load diversity into *scheduled diversity* and *call diversity.* Scheduled diversity is that diversity which is predictable as to amount and time of its occurrence and call diversity that which is predictable as to amount but not as to time of its occurrence. The character of call diversity may be discerned from Fig. 2 illustrating monthly diversity. It is evident that the day-to-day load variations make it impossible to predict the day of combined peak or the day of either system's peak. There is, however, adequate expectancy that the two systems will not have their individual peaks on the same day, *i. e.*, that there will be monthly diversity. But in order that this portion of the total diversity may result in capacity savings, and inasmuch as the necessary power interchanges cannot be scheduled in advance, arrangements must be made for a previously determined amount of diversity-power flow which can be called for on short notice by the party experiencing a heavy or peak day. On another day when the other party approaches its estimated peak load it in turn calls for this diversity flow. Hence the expression *call diversity.*

To be of value, the amount of both scheduled diversity and call diversity must be established two or two and one-half years in advance. Both are firm entitlements and firm obligations,—scheduled diversity during periods which may be scheduled in advance, and call diversity at such times as either company's loads are such as to justify calling for it.

Usually the call diversity approximates the monthly diversity; and the scheduled diversity is likely to be the yearly and daily diversity. However, to the extent that the monthly diversity has a predictable time characteristic, such as might arise from a regular downward or upward trend of the daily peak loads, it can be considered as scheduled diversity. Similarly the yearly and daily diversities may have uncertain time characteristics and would therefore contribute to call diversity.

3. Firm Power

Firm power arises when one company, instead of installing necessary generating capacity in its own system, chooses to buy power from the other system. It involves a sale contract, usually made two or three years in advance, with a firm obligation on the part of the seller to hold capacity available for the use of the buyer in lieu of installed capacity.

Short-Term and Long-Term Firm Power. Firm power may result from either short-term contracts running for only two or three years or long-term contracts extending ten, fifteen, or more years.

Under the heading of short-term firm-power contracts would be those arrangements sometimes entered into under the name of staggered construction, where one company instead of building a new power house will, for a year or two, buy its additional requirements from a neighboring company which has surplus capacity. In a later year the situation may be reversed, the first company building its generating station and selling to the other company, whose own needs by this time have more than used up its own available capacity.

Sometimes several neighboring companies will form a pool of their capacity, and stations will be developed, as dictated by economy, in the system of one company or the other for the benefit of the entire pool,—witness the power pool in and around Chicago. In such cases firm power is really flowing from one system to the other for short terms, the flows shifting back and forth from year to year depending on how the loads and capacities of the systems develop.

An arrangement by which a company obligates itself to take power for an extended time such as 10, 15, or 20 years, where it is distinctly not a temporary expedient, is classified as a long-term firm-power transaction.

Peak Power and Base Power. Firm-power provisions are sometimes spoken of as being *peak power*, or *base power*.

Peak power refers to power which is either available for only a few hours a day, or which carries an energy rate which is high in comparison with the incremental costs per kilowatt-hour of the poorer stations in the receiving system. Therefore it is used for peak purposes only. If the energy price of the purchased power is very high, and if there is no load-factor guarantee in the contract, it might even result in no energy ordinarily being used. This would be the purchase of a capacity entitlement for use only when other equipment having lower incremental costs per kilowatt-hour is not available.

Base power is power which carries an energy rate which is low in comparison with the incremental costs per kilowatt-hour of the better stations in the receiving system and therefore it is used in the base of the load curve at high-load factor. Where the energy rate of the firm power is neither distinctly high nor low in reference to the incremental energy costs of the various generating stations in the receiving system, the purchased power takes an intermediate place in the receiver's load curve, as determined by economies.

Quasi-Firm Power. Ordinarily, the expression firm power implies that the selling company obligates itself to maintain the spare capacity necessary to make the power *firm*, and therefore relieves the buying company from the necessity of providing any spare capacity for the purchased power. Sometimes, however, power is sold with the understanding that its delivery is conditional on the availability of certain special equipment. Company *A* may for instance install a generator in one of its stations and sell part or all of the output of that generator to company *B*, with the understanding that power will not be delivered if that generator breaks down. In this case, as far as *B* is concerned, *A's* generator resembles any of *B's* own generators which is liable to break down at any time and *B* must therefore provide the spare capacity for the purchase. It may be best to refer to such a transaction as being quasi-firm power, although as far as the interconnection is concerned it has all of the characteristics of firm power when it is flowing and does not warrant a separate classification.

4. Storage Power

The term storage power has been applied to transactions involving the conversion of energy generated off peak in one system into peak capacity in another system through the medium of storage. The particular storage medium used is immaterial, although in America at least and in this discussion we are practically concerned only with the medium of hydraulic potential energy.

Two classes of storage power may be recognized; that associated with pumped storage and that associated with improved utilization of stored stream flow.

Pumped Storage. In the case of pumped storage, water is actually pumped into the storage pond during off-peak hours, using relatively low-cost energy, and later that water is used for the generation of energy on peak when it has capacity value.

Improved Utilization of Storage. In the other and more general class of storage power, energy is not put into storage; instead there is a substitution for energy which would otherwise be taken out of the available storage. The available stored energy is thus conserved for utilization at a higher rate of discharge and at a time when capacity value will be created.

The present discussion is concerned only with those cases where two companies are involved and where the energy to be stored or used in substitution is transmitted over an interconnection. This energy may be generated by steam power or it may be energy from another hydro-development on the same or another stream.

The classification of storage power is mainly concerned with the creation of capacity by the conversion of energy having relatively low value. This capacity may be sent to the cooperating company, retained by the hydro company, or divided between them, depending upon where it may be used to best advantage. There may be instances, however, where energy of relatively low value is converted through the medium of storage into energy of higher value, but the savings to be realized will be small in proportion to those obtained where capacity value is created.

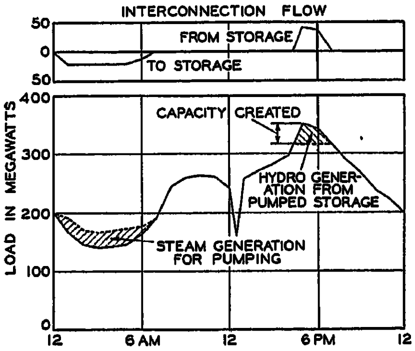

FIG. 4—PUMPED STORAGE

The power and energy quantities involved may be more readily observed in the accompanying diagrams. The quantities involved under the pumped-storage scheme are shown in Fig. 4 for the case where the capacity created is returned to the company supplying the off-peak energy. The common case of better utilization of natural storage is represented by Fig. 5, in which it is assumed that the capacity created is returned to the steam company. Fig. 6 represents the special case where two companies having similar peak characteristics cooperate to obtain the greatest capacity value from available hydro energy. The scheme depends upon the fact that the combined peak of the two companies is sharper than that of the hydro company alone and therefore that the available hydro energy will have a greater capacity value on the combined peak. In operation the non-hydro company must generate energy in addition to its own load immediately before and immediately after its peak. This requires careful load dispatching and well-conceived contractual relations.

5. *Intra-Company Use*

Intra-company use refers to use of the interconnecting facilities by one of the companies in place of other facilities which it would have had to provide for its own purposes. Interconnecting facilities which may be thus used include transmission lines and structures, substation equipment, tertiary windings in interconnection transformers which take the place of separate two-winding transformers, and rights-of-way.

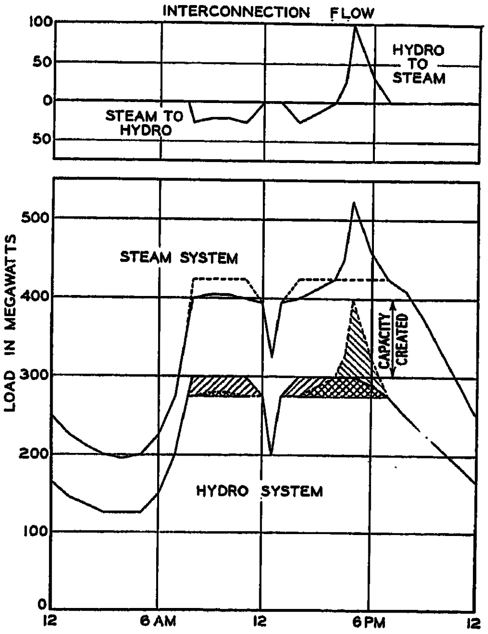

Fig. 5—Improved Utilization of Storage

Systems having dissimilar peak characteristics
———Load - - - - - - - Generation

In some of these transactions energy for intra-company use is commingled with interconnection flows and in such cases contractual arrangements are necessary to provide for their separation and to place limits upon the intra-company use so that interconnection flows are not unduly hampered. In other cases it is necessary simply to provide for division of the resulting benefits in the manner intended by the parties and there is no necessity for recognizing the classification of intra-company use so far as energy flows are concerned.

An example of intra-company use appears in Fig. 7 where the interconnection lines between the generating sources *A* and *B* of two companies are tapped so that they may be used by company *A* in transmitting energy from *A* to *M*, one of its outlying load centers, instead of *A's* reinforcing its own direct transmission between *A* and *M*.

6. *Economy Flow*

Economy flow occurs when energy used by one system and which could have been generated by it, is actually generated by another system because it is more economical to do so. For instance, if *A* has idle capacity capable of operating at an incremental cost of 3 mills per kilowatt-hour at a time when *B* is running generating capacity having an incremental cost of 4 mills per kilowatt-hour, obviously interconnection permits substitution of the less expensive generation, and the resulting transaction is called economy flow.

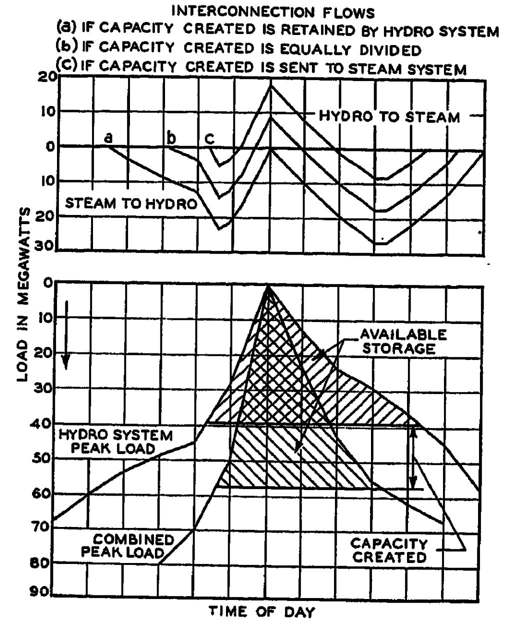

Fig. 6—Improved Utilization of Storage

Systems having similar peak characteristics

In order to determine the cost and value of power and energy thus transferred it may sometimes be desirable to distinguish that part of the transaction which results in a change in standby or fixed element of operating costs—such as might come about by its shutting down generators or boilers in the receiving system. It is suggested that the term *economy power* might be applied to this part of the transaction to distinguish it from that part in which the saving is proportional to the amount

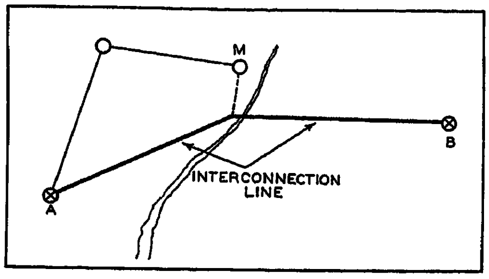

Fig. 7—Intra-Company Use

⊗ Generating stations
○ Substations

of energy transferred, which might be called *economy energy.* In some cases, as when a standby station is shut down by another company's agreeing to supply the standby service ordinarily obtained from this station, the power phase of the transaction is dominant, and the energy flows of secondary or negligible importance.

Custom has given a subdivision of economy flow a name of its own—*dump power*. Dump power is a particular economy-flow transaction in which the energy involved could not be used in the system of its origin and which if not transferred to the other system would have been wasted. It is usually associated with hydroelectric operation although it may arise also from operations where there is waste heat or gas available for electric generation.

Economy-flow transactions are usually also characterized by being on an "if, as and when" available basis or by being cancelable on short notice.

7. *Unintentional Flow*

In the present state of the art, especially where a network of interconnections is involved, the flow of energy cannot be or may not be controlled exactly as intended. Where 20,000 kw. is intended to flow, 22,000 kw. may be found to have passed; where two systems are merely operating in parallel with no interchange intended, inadvertent flows may occur. Such energy quantities cannot be entirely disregarded since they cost money to generate and they save money for the receiving company. It is therefore convenient to recognize unintentional flow in the inter-company relations.

II—EVALUATION

Before decision can be reached as to whether or not a proposed interconnection should be installed, it is necessary to estimate and present its economies.

Examination of load data and operating characteristics of the two systems in the light of the foregoing classification of services will perhaps indicate that interconnection will make unnecessary the installation of certain amounts of capacity. The resulting avoided investment in generating stations must be compared with the capital cost of the interconnection. The avoided annual fixed charges must be compared with the fixed charges and operating expense of the interconnection. The change in the annual generating station production expense brought about by the various services must be determined. The comparisons mentioned must be made ordinarily not for only one year, but for an extended period, probably not less than five years nor more than ten years, for the reason that wide variations may occur in the amount of the savings from year to year.

If the result of these comparisons is a net saving the decision would probably be favorable to making the interconnection. If the net saving is small or slightly negative, it does not follow that the interconnection should not be made. Consideration of the intangible and indeterminate benefits may warrant favorable decision. Among such indeterminate benefits may be mentioned catastrophe assistance, lessened hazard from under-estimation of loads, possibility of taking chances on the non-availability or non-installation of equipment which could not be taken without interconnection, and opportunity for future but at present unforeseen benefits.

The following is intended to indicate the general procedure and the mode of attack to be used in evaluating a proposed interconnection.

1. *Generating Capacity Savings*

From the load data and operating characteristics of the systems it will be determined that certain capacity savings are to be realized by taking advantage of the various services which have been enumerated. For instance, the availability of emergency service may make it possible to reduce the spare capacity from 20 or 25 per cent to 15 per cent, or from 15 per cent to 10 per cent; or, where it had been thought necessary without interconnection to have three spare generating units, with interconnection it may be decided that two units will suffice. Ordinarily the saving which results from emergency service is determined by the exercise of judgment rather than by any rule. If there is load diversity in the interconnected systems this results in a comparatively definite capacity saving. Similarly, the opportunity for storage-power transactions yields a determinable capacity saving. Firm-power transactions theoretically at least, do not result in a net capacity saving as they simply involve installation of capacity in one system rather than in the other. In actual practise, however, due to the fact that installations are made in relatively large units of commercial size, there may be a capacity saving from this source.

In fact, if the problem is one involving only two or three years it is safer to determine the actual capacity installation program with and without interconnection, rather than to use the capacity savings theoretically indicated. However, if the benefits of the interconnection accrue over a long period of years, during which it is expected that the business will continue to grow, a study based on commercial unit sizes is not of any superior value. The error arising from not considering commercial unit sizes is present in both the with-interconnection and without-interconnection programs and in the comparison the errors tend to drop out. In any event they become unimportant over a period of years. Further, the impossibility of predicting specific installation programs with any adequate degree of accuracy for more than a very few years in advance, favors the use of the theoretically indicated amounts of capacity saving.

In arriving at the capacity savings in any detailed study it is necessary to consider conditions month by month as the theoretical capacity saving may vary cyclically within each year.

Another caution to be exercised in arriving at the avoided capacity is to consider the effect which the requirements of scheduled outage of units for maintenance will have on the possible savings. This effect will be of importance only if the seasonal variation of the combined load is small.

2. *Capital Cost Savings*

After the amount of capacity saved has been ascertained, the resultant capital cost saving must be determined. This may be accomplished by applying appropriate unit costs to the kilowatts of avoided capacity or if a more concrete study is being made, by setting up the particular program of station installations "without interconnection" together with its capital costs, then doing the same for "with interconnection," and finally obtaining the difference in capital costs.

Of course any capital savings which result from intra-company use of the interconnecting facilities, or from firm-power transactions, must be taken into account.

It remains then only to compare the total capital cost savings with the capital cost of the interconnection.

Rarely is a determination of capital cost savings sufficient *per se* to indicate the economic merits of an interconnection. Nevertheless, capital cost determinations must be made as the first step in computing the annual costs, and they are in any event of importance to the executives who are concerned with financing the project.

3. *Annual Fixed Charges*

In the evaluation of an interconnection the determination of its effect upon fixed charges is necessary since any avoided investment in facilities naturally results in a reduction of fixed charges and on the other hand fixed charges on the interconnecting facilities are incurred.

The term *fixed charges* is ordinarily meant to include the annual costs of money, insurance, taxes, retirement expense and general expense, and in the case of facilities other than generating stations, it is sometimes convenient to include operation and maintenance expenses. Fixed charges are usually determined and expressed as a percentage of capital cost.

The necessity for careful determination of fixed charges warrants some discussion of the fixed-charge percentage to be used in each case.

Money Cost. The annual cost of money represents the compensation which must be given to capital in order that it be attracted to the industry for the purposes under consideration. In the absence of abnormal conditions, it is likely to be the prevailing allowable return on public utility property. This is neither the cost of borrowed money nor the yield on equity funds, but rather the weighted-average cost of all funds. There may, however, be cases where the cost of the next increment of financing should be used. If this happens to be by bonds, the money cost includes not only the coupon yield, but also the amortization of debt discount and expense.

Insurance. Insurance includes the cost of fire, tornado, earthquake, public liability, boiler, machinery, fly-wheel, workmen's compensation and other insurance. Insurance should also include the cost of self-insurance. Where the company's operations are large or have continued over an extended period of time the cost of self-insurance can be estimated from the actual losses incurred for which insurance premiums might otherwise have been paid.

Taxes. Taxes differ in each state and municipality and in order to arrive at the proper percentage it is necessary to understand the manner in which the taxes are levied. In many cases it is necessary to determine only the relation of the total state and municipal taxes paid by the company to its fixed capital; in other cases the tax rate in a particular locality should be applied to facilities in that locality. In still other cases, where taxes are levied on the gross receipts of a company and would not be directly affected by any interconnection considerations, they may be ignored. In all cases, however, income taxes should be included. Because of the manner of income tax determination the relation between borrowed funds and equity funds must be known and the prevailing tax rate applied to only the taxable income. For example, with the present U. S. federal income tax of 12 per cent, if the money cost is 8 per cent and 60 per cent of the capital funds are borrowed at a cost of 5 per cent, the taxable income will be 5.682 per cent and the income tax 0.682 per cent of capital.

Retirement Expense. Retirement expense should be determined on the sinking-fund basis using the rate of interest currently earned on securities suitable for investment in trust funds. The retirement rate to be used will depend upon the rate of interest and the economic life of the equipment under consideration, which varies for different classes of equipment. If the rate of interest is 5 per cent per annum, the retirement rate for a steam generating station having an economic life of 18 or 19 years will be 3.25 per cent or 3.50 per cent; for a hydroelectric development having, due to its inherently simple and sturdy construction and high efficiency, an economic life of 50 years, only 0.5 per cent; for a substation having an economic life of 22½ years, 2.5 per cent; and for a transmission line having an economic life of 25 years, 2 per cent.

General Expense. General expense includes administrative salaries, general office expenses, communication, law expenses, relief and welfare work, and other items not included elsewhere. Ordinarily general expense will amount to 1 per cent or less, of fixed capital, but frequently it may be considered that general ex-expense will be unaffected by interconnection.

Usually fixed charges on interconnecting facilities, exclusive of their operation and maintenance, will be slightly less than on steam stations, so that for the same capital investment there is some saving on this score. Naturally no generally applicable fixed charge percentages can be cited. Fixed charges must be individually determined for each case. However, to indicate the order of the fixed charges it may be said that for steam generating stations they will frequently be about 12 or 13 per cent and for hydroelectric developments perhaps 9 or 10 per cent. For steel-tower transmission lines fixed charges are affected somewhat by the proportion of the investment in right-of-way but they may run from 12 to 14 per cent with operation and maintenance expenses included. Substations, likewise including operation and maintenance expenses, will be somewhat higher, usually between 14 and 17 per cent.

4. Annual Production-Expense Savings

After the saving in fixed charges has been determined it remains to evaluate the effect of interconnection on production expense. This requires, first, determination of station load schedules with and without interconnection and, second, application of the individual station production-expense formulas to the end that the changes in the fixed and variable elements of production expense be determined.

Station Load Schedules. The output of each station and the character of its load for most economic conditions with and without interconnection can be obtained by resorting to integrated duration curves or duration curves, for the loads of the individual systems on the one hand and for the combined system on the other, on an annual, seasonal, or monthly basis, according to the degree of precision desired. Integrated duration curves with percentage scales are helpful where much work is to be done. (See Hutchinson, A. I. E. E. TRANSACTIONS, 1914.) For more precise studies loading schedules may be obtained from ordinary load curves of typical weekdays, Saturdays and Sundays. Due allowance must be made for the outage of generating units for normal and abnormal maintenance. It must be remembered that the interconnection transactions will be limited by transmission losses, the capacity of interstation and interconnection transmission, the necessities of service protection in local areas, minimum steaming conditions, and the minor imperfections of operation and of contracts.

Behavior of Generating Station Costs. Before the production expense savings due to interconnection can be determined it is necessary to know for each generating station in the interconnected systems, the behavior of production expense as a function of station output. For interconnection studies the two-part annual production expense formula has been found to be sufficiently accurate and most suitable. Such a two-part formula arises from the experience that within a limited range of annual capacity factors the production expense is made up of a fixed element independent of annual output and a variable element directly proportional to the number of kilowatt-hours generated in the period. The fixed element includes a large part of the items of superintendence, supervision, labor, supplies, and maintenance, together with (usually) a small part of fuel expense. The variable component consists principally of fuel costs, although part of the maintenance and small amounts of other items may also be found to come in this class. Expressed in mills per kilowatt-hour it represents the average cost throughout the year of generating an additional unit of output, and is therefore commonly termed the "incremental cost."

Usually a single formula covering a limited capacity-factor range suffices for each station. If, however, the station is to be examined under widely differing capacity factors a two-part formula for each of several capacity-factor ranges may be necessary. If the station is to operate at a peak load predominately less than its capacity, as may be the case with the poorest stations, corrections may be necessary principally in the fixed element of the two-part formula, or a formula introducing a peak-preparedness term as developed by Funk and Ralston (Philadelphia Electric Company) must be used.

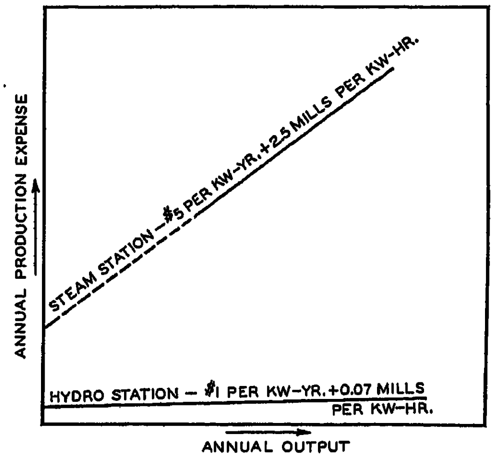

FIG. 8—ANNUAL PRODUCTION EXPENSE CHARACTERISTICS FOR STEAM AND HYDRO STATIONS

Fig. 8 is representative of the two-part formula for a steam station having a fixed element of about $5.00 per kilowatt of installed capacity and a variable element of about 2½ mills per kilowatt-hour. For comparison a hydro-station formula with a fixed element of about $1.00 per kilowatt of installed capacity and an almost negligible variable element is shown.

A bibliography of the scant but authoritative literature on this subject is attached.

Fixed Element of Production Expense. Obviously the avoidance of an installation of generating capacity brings about a reduction in the fixed element of production expense. Approximately speaking, and frequently with sufficient accuracy in the case of a long-term study, the saving in fixed-element expense is the number of kilowatts of avoided capacity resulting from the interconnection transactions multiplied by a figure, possibly between $3.00 and $5.00, representing the fixed element of production expense per kilowatt of avoided capacity. Its effect is similar to avoided fixed charges.

For a more precise determination in which actual installation programs and station loadings have been predicted, it is advisable to tabulate and add the appropriate fixed elements for all generating stations under the without-interconnection condition and then under the with-interconnection condition. The difference between the two will be the fixed-element saving. In such precise study it may be recognized that, aside from fixed-element saving on avoided capacity, there is sometimes an additional saving of fixed costs in the marginal stations due to the interconnection's encouraging curtailment of *running* spare capacity.

Variable Element of Production Expense. The change in variable element of production expense involves only the multiplication of the energy quantities determined for each generating station without and with interconnection, by the corresponding increment cost per kilowatt-hour from the two-part formula and obtaining the difference between the two plans of operation.

Frequently the net effect of interconnection on this item is not a saving, but a decided loss. The explanation is, of course, that the interconnection forestalls installation of modern, highly efficient equipment, and increases the duty on older plants having higher variable costs.

5. *Net Savings*

Net savings resulting from the interconnection are obtained from the combination of net fixed-charge savings and net production-expense savings, which may well be presented by means of a tabulation showing the amount of these savings for each of the years studied. If comparisons are to be made between different plans of interconnection, these net annual savings over the period of study should be accumulated and due account taken of interest on the accumulations.

No attempt has been made herein to show how savings may be divided between the interconnecting parties, since this is a matter for agreement between them. Nevertheless it is a factor which may affect some of the items of evaluation, and certainly requires careful recognition of the equities for each particular class of interconnection service in the agreements relating to the project.

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Discussion

For discussion of this paper see page 1280.

Interconnection—New England District

BY E. W. DILLARD[1]
Member, A. I. E. E.
and
W. R. BELL[1]
Associate, A. I. E. E.

Historical and Physical Data

THE geographical characteristics and the early method of development of the New England region make it a natural field for interconnection. The total area covered is small compared with that of other interconnected districts, but industrial growth has been intensive and many strong local companies have been developed. There are tidewater locations for steam plants affording ample condensing water and low carriage charges for fuel, and there are inland rivers with sufficient runoff, fall and control possibilities to make water power developments of various types attractive. It is natural that a close network of tie lines has been built.

The standpoint of those companies which now form the New England Power Association, together with that of the systems directly interconnected with the Association, has been taken for the sake of brevity and in the belief that their experiences are typical of the territory. The experience of the companies now forming the Association is somewhat unique in that many of them were interconnected when operating under separate financial control. A direct comparison of the economies of both methods of operation is therefore possible. The companies operating in the state of Maine have been generally interconnected presumably for the same purposes that have existed in the remainder of New England, but they have been isolated as a group by legislative restrictions upon the flow of power across the boundaries of the state.

The New England Power System started principally as a hydroelectric system with plants on the Connecticut and Deerfield Rivers located in the northwestern part of Massachusetts and southern Vermont. Lines were built easterly through major cities and towns terminating near Worcester. Steam reserve was obtained from the local companies to whom power was sold, and also from some large industrial purchasers. Later, transmission was extended into Rhode Island, connecting with Woonsocket, Pawtucket, Providence, and Fall River. The first major interconnection (of about 30,000-kva. capacity) was made in 1913 at an existing crossing with the lines of the Turners Falls Power & Electric Company. The Turners Falls Power & Electric Company had considerable surplus hydro output at times which the New England Power system was able to absorb, and in addition was occasionally able to sell steam auxiliary. This tie, in view of the small amount expended, has probably shown a greater return per dollar invested than any of those subsequently made. It later provided a path in the reverse direction to market large quantities of surplus steam capacity, and still later some firm power has been sold through the tie.

The South Street steam plant in Providence was next connected with 20,000 kva. of cable capacity. This tie furnished a source of steam supplied largely from spare capacity, and also a market for surplus hydro power. After a few years an additional 50,000-kva. high-tension tie was made here and an elaborate agreement was drawn with the Narragansett Electric Company of Providence under which firm and surplus steam power was purchased particularly to cover large industrial contracts in that general territory.

The next major connection was with the Montville steam plant of the Eastern Connecticut Power Company (now the Eastern Division of the Connecticut Light & Power Company). This arrangement involved about 60 miles of line, which was partly in the New England Power System territory and partly in the Eastern Connecticut territory, and served, especially in the case of the Eastern Connecticut Company, as a source of power to customers along its length. The extra expense due to the larger capacity built into the line for power transfer and also some charges on account of additional boilers to make available the capacity of a spare unit at Montville were carried by the New England Company. As part of this arrangement, it was possible for the New England Power System to purchase at any time when the unit was available, a reasonably firm quantity of steam generation up to 10,000 kw. This connection was made during the period of extraordinary growth of 1919 and 1920 when costs were high and development of hydro would not have been economically sound.

A similar arrangement was made with the Edison Electric Illuminating Company of Boston at approximately the same time, making available to the New England Power System surplus capacity in the "L" Street station of this company, to the extent of 15,000 kva., as well as a market for surplus hydro power. The charges on Edison's expense were carried for a number of years by New England. Afterward this line developed into a customers' line for both parties, as well as remaining an interconnection.

In 1924 negotiations were carried on with the then Adirondack Power and Light Company for a connection between systems. The New York State Company at that period had primarily an unregulated hydroelectric system. The New England Power System had grown to approximately equal parts of hydro and steam, and the hydro was largely regulated so that it could absorb up to 50,000 kw. of surplus hydro from New York State. The construction of this tie established conditions whereby, for the first time, three systems were involved in power transfers because much of this water generated power found its way through the New England Power System to the Edison company at Boston. Each company carried the expense of transmission in its own territory with a slight adjustment for inequality of length.

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[1] New England Power Engg. & Service Corp., Boston, Mass.

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An additional interconnection was made in 1927 with the Edison company at 110,000 volts which connected its new Edgar plant with the system center at Millbury. Both parties covered the expense of the line in their own territories. With this line it was possible to transfer up to 50,000 kw. of low cost steam from the Edgar station to the New England Power System. No contract was made.

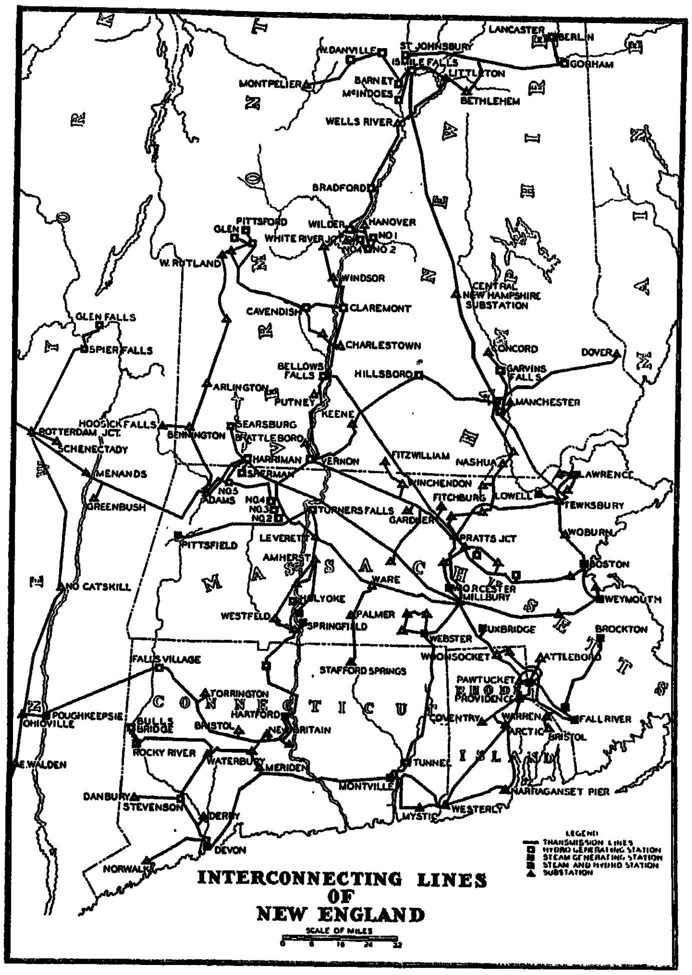

Fig. 1

In 1929 prior to the development of Fifteen Mile Falls, and prior to the sale of a large block of primary power to the Edison company on the north side of their territory, it became a matter of mutual saving to backup the northern territory of the Edison Company through the New England Power System from the connection already made between Millbury and the Edgar station on the south side of the territory. New England advanced its own construction schedule one year and built, prior to the necessity on account of Fifteen Mile Falls power, a connection from Millbury to the north side of the Edison territory.

In addition to the interconnections between the New England Company and adjacent systems, there are at least two major interconnection arrangements in operation; that of the Connecticut Valley Exchange Board, and the Montaup Electric Company.

The Turners Falls Power & Electric Company, taking its power mainly from a large hydro plant in northern Massachusetts, was early connected with the local electric company at Springfield, Massachusetts, which depended primarily on steam power. In 1925, the Connecticut Valley Exchange started operation involving the Hartford Company with the two mentioned above, and in the following year included power transfer with the Connecticut Light & Power Company in the southwestern part of Connecticut. The Central Hudson Company was interconnected in 1927. These companies, without common control, arranged to operate their power facilities as a group, at first under general orders from a small organization formed for the purpose, and later by actual dispatching.

The pool was charged the cost of generation in excess of local requirements by each company furnishing power to it. Each company was charged for power received from the pool an amount equal to the cost that company would have incurred in producing the same amount in its own plants. The expense consisted of management costs and some fixed charges for interconnection. The New England Power System is physically connected through the Turners Falls Company, and has in late years exchanged power with the pool as a unit.

The Montaup Electric Company, which is controlled by the local companies at Pawtucket, Woonsocket, Brockton, and Fall River, started operation in 1925. A steam station and transmission lines connecting the participating companies were built. Capital was furnished by the local companies in proportion to their capacity requirements, and the operating expense was paid for by sales at cost to the local companies. The New England Power System is connected to and exchanges power with the system as a unit.

The reasons for the construction of these interconnections are: (1) The absorption of surplus hydro power from systems generating, largely, from unregulated hydro sources: (2) The absorption of large quantities of surplus steam with resultant good load factor on relatively high-grade steam plants of adjacent systems: (3) Arrangements for the purchase of surplus steam capacity in various stations which resulted in a certain amount of firm capacity: (4) The sale or purchase of firm power.

Benefits Derived from Interconnection

Peak Diversity. Companies which are not under the same financial control have not taken advantage of peak diversity by virtue of interconnections to save capacity installation. Each company has assumed responsibility for its own primary load. A study of this subject indicates that between the major interconnected groups in New England there is approximately 5 per cent diversity, amounting to say 50,000 kw. A worthwhile safety factor is gained though by each of the interconnected companies, and it has become practise to take advantage of this by continually tying together, even though an exchange of kilowatt-hours is not particularly desirable at the time and may even result in some slight losses.

On the other hand, there is an appreciable diversity saving between the commonly owned and controlled properties such as Lowell, Lawrence, Worcester, Providence, and the original wholesale company, known as the New England Power Company which is of the order of 7 per cent, or at the present time about 30,000 kw. This diversity exists on account of peaks occurring on different days, rather than at different hours of the same day.

A large diversity of peaks in the same day might well be looked for on a system spread into two time belts but no dependable diversity of this sort appears from a study of the New England systems since they all operated on eastern standard time except during summer months when heavy peaks are not to be expected.

Reserve Diversity. No particular advantage is taken of reserve diversity. The systems usually carry reserve equal at least to the capacity made unavailable by the loss of their largest units. The New England Power System carries a percentage of operating spare, generally 10 per cent or more, which is greater than the effect of losing its largest unit. Probably some of the smaller systems connected do take some advantage of reserve diversity, but generally the gain is considered as a matter of additional safety to service. The effect of a loss of unit, or of a major connection supplying power, is greatly reduced by spreading the effect over the two or three remaining systems connected. In general, it has been demonstrated that the loss of 25,000 to 50,000 kw. on the system results in less than 1/10 of a cycle frequency drop.

Emergency Interchange. Conditions necessitating emergency interchange may be brought about by loss of stations, low water, or fuel shortage. Parallel operation of systems at all comparable in size is a desirable procedure and the interconnected companies have been desirous of keeping ties closed as much as possible. All companies have been saved from embarrassing situations by this practise. In our case emergency interchange has been most useful on occasions of a system pull-out, when, during an attempt to transfer for economic reasons too large blocks of power over lines of limited capacity, some upset has caused these lines to trip and in this case, the end of the system lacking capacity has been partly supported by the interconnection. One case out of many which could be cited may be of interest. The New York Power & Light System some time ago requested an unusual amount of power to assist them in sending power west to replace the loss of a machine in the Buffalo-Niagara district. The Boston Edison Company was readily able to supply this deficiency for the time required and each system between relayed the power. The best of relations obtain in this matter and we know of no cases where any special charges have resulted on account of this sort of service. In the early days when standards of service were not as exacting as they are today, occasionally when requested one system lowered its frequency in order to phase with and assist in supporting an adjacent system which had lost capacity.

Low water is not classified as an emergency because all the major systems connected have water power sufficiently relayed with steam or purchased power.

During various periods of fuel shortage, the New England Power System, with the exception of the winter of 1917-1918, has been fortunate enough to obtain sufficient fuel for its own plants. It has taken advantage of some of its interconnections by arranging to supply fuel to interconnected steam plants and in turn to receive power at prearranged prices. Another advantage of interconnection in regard to fuel supply has been the possibility of converting the South Street Station at Providence to more or less a base load plant, although the storage provisions at that plant have not been enlarged so as to become comparable with the larger outputs. It has always been known that with a temporary fuel stringency at that point, power could be generated elsewhere, even though at a slightly increased cost.

Firm Sale. Some of the New England interconnections have developed into means for primary sale, and likewise connections built for primary sales have resulted in considerable interchange of power of other than a primary nature.

The contract terms have been made of varying lengths. It is often possible to make a considerable saving in providing firm capacity by arranging with an adjacent system, which is for the time being overdeveloped, or which has been willing to make an apparent over-development because of joint economies. An outstanding example is the development of Fifteen Mile Falls lower plant at a time when the need of additional capacity on the New England Power System coincided with that of the Edison System at Boston. This made possible the development of a large and economical block of power and insured its rapid absorption with a consequent saving to both parties.

Likewise, within the New England Power System, power contracts have been made between the wholesale companies and many of the local retail companies, which have resulted in a conservation of natural resources and joint benefits by the selling of water power, or tide water steam generated power to the smaller companies. The smaller companies gain by the ability to make commitments for only one or two years in advance, rather than make relatively large station extensions which would require many years to absorb.

Intra-Company Use. It has been possible to use the transmission facilities in a number of cases to supply a customer of an adjacent system at a point remote from their lines. For a number of years the New York Power & Light Company furnished a customer in the neighborhood of Lake Champlain through our system and that of the Central Vermont Public Service Company until, as has recently become the case, it has proved economical to construct lines to serve the load directly.

A number of instances has occurred where interconnections between systems have been made at more than one point. It has always been possible to pass emergency power through the adjoining system in order to back-up a section of the first system adjacent to one of the ties.

Economy Flow. The use of interconnections for economy flow or as it is sometimes called, exchange power, has shown a real financial return. It may be generally said that in New England and in adjacent systems in New York State that there is no operation of uneconomical steam when economical steam or surplus hydro is available, provided transmission facilities are adequate and there is no especial need for backing up local service by local generation. The New England Power System has made a practise of purchasing power which could be generated at less cost in plants other than its own furnishing power to adjacent systems where it could generate for less cost, or furnishing power from one system to another across its own lines. Any saving resulting from this sort of operation is generally divided between the systems involved; if the transaction is between two systems, half of the saving goes to each; and if among three, one-third of the saving goes to each. Transfers of this sort in and out of the New England System amount to several hundred million kilowatt-hours in a year.

Some of the system steam plants are operated during the day and evening hours in some of the larger communities where tie lines are not wholly adequate. These plants operate usually at approximately one-half of the local load and with standby capacity just sufficient so that the entire load can be carried in case of any sudden emergency. Other than this so-called "service steam" the generation is distributed strictly on an economy basis. Service steam operation will disappear when system ties become sufficiently reinforced to provide the necessary reliability.

Contract Relations

The New England Power System was primarily benefited in the earlier connections by the ability to purchase auxiliary power and it was customary to make a guarantee to purchase a block of kilowatt-hours for a number of years. This guarantee of taking power was backed by a forfeit, in case of failure to take power, sufficient to cover the expense involved by the interconnection. Later, the character of the use of the lines shifted to that of a straight interchange basis with the facilities becoming more useful for serving customers in the territory through which they ran, and forfeits became less necessary.

The Providence contract gave the New England Power System the right to purchase the surplus capacity of the station when available and firm capacity to the extent of a certain minimum reservation. New England paid for the reservation a predetermined percentage charge on the book value of the plant and for kilowatt-hours at a slight margin over the average operating cost. The Providence Company agreed to purchase surplus at a margin of saving.

The connection to New York State and the later connection with the Edison company were put in with no advance agreements for interchange of power because it was apparent to both companies that the expense of the ties would be covered by the business over them, based on each company's knowledge of each system and the generating facilities that existed.

In the early days, prices were usually agreed upon from time to time, to be effective for certain periods and for certain classes of power. These often remained constant for periods of a year or more. If either company felt that the price was unjust, the matter was brought up, discussed and adjusted. This method was generally applied to comparison of cost of surplus hydro to steam generation, and is still used for steam and hydro exchange with smaller companies where the benefits would not warrant the bookkeeping involved for a refined method.

More recently the major systems interchange has been made between steam plants and it has become necessary to go thoroughly into the increment and decrement cost of power. A definite man has been designated on each system and he furnishes necessary cost data to the dispatching departments interested. Representatives of the various interested parties get together at the start of these arrangements and from time to time during their operation to insure fairness and acquaint themselves with the methods employed. All methods have not yet become identical, but are sufficiently close so that each company feels satisfied with the intent of each of the other companies. This procedure has resulted in a really remarkable amount of business between the dispatching departments, entirely based on these estimated increment and decrement costs. The New England Power System's primary business amounts to approximately one and one-half billion kilowatt-hours per year, and exchange of this type from and to the system now amounts to around 300 million kilowatt-hours. This sort of transaction, of course, is only practicable where there is a reasonable difference in the costs of power generation.

The extreme differentials, for example, are represented by high-pressure stations on tide water, as against older and inland steam stations, and make a spread of several mills. No interchange is attempted with a differential of less than 2/10 of a mill, in view of the uncertainty in estimating costs accurately.

Plans for interchange are usually made daily in advance, so that definite schedules can be arranged late in the afternoon for the following day. The New England Power System dispatcher is in touch with the dispatchers of the adjacent systems and determines the quantities and values of power which can be furnished or absorbed. These, compared with his own sources and costs, readily determine the economical set-up for the day and schedules are arranged. As stated above, where power is exchanged between two companies the saving that results is split equally, the line losses coming into the calculations as part of the cost where they are of sufficient importance.

When it is impossible for the New England Power System to participate in exchange to advantage with two adjacent systems and there is advantage for the adjacent systems to interchange power, arrangement is made on what is known as a three-way basis, in which it is assumed that the transmission company is a necessity to the transaction; therefore the profits are split among the three equally.

There is, of course, some difficulty in all these transactions in attempting to make the power flow exactly as intended and it is not unknown to have it reverse for short periods. In periods when companies are tied together and there is no intent to exchange power, some exchange may occur in an unprofitable direction. All these losses are deducted from current gains, and no effort is made to return the kilowatt-hours which may be received in this inadvertent manner.

The complicated procedure of estimating saving which involves backing down machines, shutting down machines, banking boilers, saving of additional boilers on the line, added or saved maintenance, together with complications of metering where a line is used for both primary and exchange power simultaneously, have forced the dispatching departments to become bookkeepers and accountants in order to turn over adequate data to the billing departments of their respective companies.

Generally there is no guarantee of services to be rendered in other than contracts for firm power delivery. It is, however, understood that each company will assist the other in an emergency, and if one company has arranged to furnish another company with power, and unforeseen conditions make it undesirable for it to do so, it will nevertheless continue to furnish the schedule planned until the other company can make arrangements to carry the load.

Contracts have been desirable when a definite saving can be made by pooling capacities but kilowatt-hour interchange or "economy flow" has been quite effectively taken care of by the operating personnel without contracts. Certain officials in each company are given authority to complete arrangements binding for a sufficient length of time to accomplish the transfers desirable. These can always be stopped if they do not appear to be working in a fair and profitable way. Fortunately, relations between companies have been pleasant and without such good will it would be impossible to carry on interchange either with or without contracts.

DISADVANTAGES AND DIFFICULTIES

We do not believe that any disadvantages have come about in any interconnection in New England that are not offset entirely by benefits derived. The major difficulty is probably in being unable to exchange power in exactly predetermined amounts with a number of other systems at the same time. The New England Power System has done a great deal of business with the Connecticut Valley Power Exchange as a unit, which in turn has frequently been interchanging power with the Central Hudson Gas and Electric Company, which is tied nearly all the time with the New York Power & Light on the north, and Metropolitan Edison and others on the south. It is believed that in order to reduce the difficulty of departure from schedule to a minimum all systems should attempt to run with rather exact speed control at 60 cycles. By allowing one system to assume responsibility for this speed control, and the other systems each to look out for the exchange over the connections, we have been able to control interchange reasonably well.

Several of the major systems are giving time service and the combined problem of correcting time and maintaining 60 cycles is a difficult one for unavoidable things shift the systems away from exact time, and the necessary correction sometimes upsets tie line control. This has been minimized by arranging for the dispatcher to know daily the time error on the systems adjacent and to adjust his time at a very slow rate to normal, when he can do so by agreement with the adjacent systems, or to adjust when separated from them.

It is not uncommon for systems all the way from Boston west to Niagara Falls, and south to Philadelphia, to operate in parallel and it is therefore necessary for word to be passed from dispatcher to dispatcher concerning the shifting of tie line loads and the taking over and changing of the point of master speed control. The large distances involved make communication of utmost importance and require the best efforts of all the companies involved, so that there may be no undue delay in passing essential information from one end of the interconnected systems to the other.

It is inevitable that there will be cases when because of special conditions the interchange schedules have not been adhered to strictly and one company or the other feels that it has been put to some disadvantage.

It has been found that informal meetings between one or more operating men representing each system involved, immediately following major occurrences of this sort, have had a highly satisfactory result in smoothing out and preventing recurrences of such difficulties. At these meetings, usually in New York City, which are called together by a temporary chairman, the various representatives present all the available data in the way of charts and records, showing exactly what did take place during the time when difficulty was experienced. It has usually been easy to trace the trouble to its source. It has been possible to come to some agreement in every case, or to outline a policy which will largely eliminate future troubles of the same nature. The utmost frankness has always prevailed and the helpful spirit of the various company representatives has made progress possible.

We have had for 10 years an association known as the "System Operators of New England" which has usually held four meetings a year and these meetings have enjoyed the heartiest popularity. The meetings are intended to bring the dispatchers of the different systems together personally, but many other officials and those most intimately responsible for the day-to-day operation of adjoining plants and systems have been interested enough to attend.

While the lack of a common financial control is not necessarily a difficulty and is certainly not a disadvantage to interconnection, it should be pointed out that the common control of interconnected units will generally work toward additional economies over straight interconnection. Effective peak diversity, better coordination of system planning, benefit of direct action, and other kindred betterments accrue. Interconnection establishes gains in operating economy and improvement in service reliability, and common financial control of interconnected companies carry these advantages a step further.

CONSTRUCTION PROGRAM BASED ON JOINT PLANNING

The New England Power System has had the good fortune to have had many alternatives in planning additional sources of power. There have been possible water power developments of various types as well as a variety of methods of extending steam generating facilities. The development at Fifteen Mile Falls was of such a size that it could not be justified without various interconnections to assist in its absorption. Its character is such as to make it a desirable adjunct to any system depending entirely on steam and this fact made it possible for us to sell a large block to the Edison company of Boston.

The New England Power System load has grown to a size in which the capacity and power requirements for growth should not be studied as a whole but divided into three major classes: (1) base load; (2) 2,000-hr. power or day load; (3) peak and spare capacity. These various classes of load grow about equally on a percentage basis but the short hour type of load grows far faster on a quantitative basis. Additonal requirements of base steam of the best grade grow slowly and if this type of plant is increased too far in advance of requirements it crowds into short hour use expensive plants designed for better load factor. For the second class, day load or 2,000-hr. power it si apparent that plant capacity should be secured for a lesesr first cost than for class one. A few hydro possibilities are peculiarly suited to this service. If the hydro plant site affords sufficient storage, permits the power house to be close to the dam and does not restrict its size, the increment first cost of unusual capacity may be favorable. These conditions existed at the Fifteen Mile Falls development. The water available at this plant, though sufficient to operate at full capacity but 2,000 hours per year, can be used when it is most valuable and involves a negligible operating cost for additional capacity.

The third requirement of the systems is for a capacity suitable for meeting annual peaks and carrying day to day spare through the year and during the peak period. The necessity of this sort of facility has been well illustrated by the development of the Rocky River Pumping Plant of the Connecticut Light & Power Company. The Fifteen Mile Falls plant is also well adapted to supply this type of power. While the older and rather uneconomical steam plants are also suited to this type of service, the cost of being ready to serve for peaks and spare is higher than that of suitable hydro plants. The Fifteen Mile Falls type of plant will confine their use for this purpose to a very small part of the year.

Interconnection, therefore, has made possible a large development of a character of power which was decidedly the type needed on the New England System which also fitted well into the Edison system but which would not have been feasible of development without a very large or interconnected system. It has made the entire output of this development more immediately useful, and put off the construction of further base load steam capacity, which will in turn be desirable to construct in large blocks and which will be more economically absorbed later, in the combined New England systems.

FEATURES OF DESIGN

Frequency Control. In the early days of interconnection no special efforts were made to control frequency beyond those which were in use on individual systems before they were tied together. It was found desirable, however, in the interests of maintenance of desired interchange schedules to hold the combined system speeds within closer limits than were found practicable by manual and natural governor control whether hydraulic or steam.

Considerable developmental work was done on the New England Power System as far back as 1927 in conjunction with various manufacturers of automatic equipment, and it is believed notable success has been obtained. Special apparatus has been installed in three hydroelectric plants in order that it may be possible for a great many hours of the year to have at least one of the plants in position to handle the major burden of speed control.

On any system of hydroelectric plants of varying characteristics, it is undesirable to place the control of speed constantly in the same plant. A run-of-the-river type of plant should be operated wide open during flood periods while during the lower water periods it may be used to carry the swings of load and the characteristics of plants using stored water are directly opposite for they are normally shut down during flood periods and used heavily during dry periods. Thus, by having automatic apparatus in key plants of various types, it is insured that one of them will almost always be available for speed regulation without departing materially from its normal economic schedule.

It has been found that a frequency deviation from normal of not more than ± 1/20 of a cycle approaches the best possible conditions for load interchange. Regulation as close as this on a scattered group of small hand controlled plants would place a burden on the operators that would be almost impossible, and even the best governors are unable to maintain the speed within such close limits. Automatic frequency control has also been found of considerable help in maintaining accurate time as recorded on the large number of synchronous clocks in the New England area.

While considerable work has been already done, it is thought we must equip more plants with automatic apparatus, so that the burden may be as widely distributed as possible, with a view to less wear and consequent maintenance in any one place, and less operation at a lowered efficiency, which necessarily follows when the load of any given units is constantly changing over rather wide limits.

TRANSMISSION

The increasing interconnection of transmission lines together with the increasing use and reliance upon electric power is necessitating always greater reliability and freedom from disturbances. Not only is it necessary to isolate disturbances closely and quickly but it is also necessary to avoid them in so far as it is economically possible. A comprehensive interconnected system will serve customers to whom a voltage surge is as disastrous even as an interruption of short duration.

Lightning disturbances present our most formidable problem and this problem is one of the most important before the industry today. It is not always possible to greatly benefit the performance of lines already in existence although in one case it was possible to add insulation and ground wires to an existing line so that it is now experiencing only about 40 per cent the lightning disturbances that it had previously. Considerable advances have been made that are particularly applicable to new construction. We are attempting to design lines with unusually short spacing of supporting structures so as to get a low average height above ground and we provide these lines with overhead ground wires where we are justified economically. Horizontal construction with single-circuit towers and two overhead ground wires are being used generally on all major lines. The importance of low footing resistance has been recognized but so far it has not been possible to arrive at any economical solution of the naturally high resistance conditions that pertain generally throughout New England. Steel grillages for tower footings have been used, however, for a number of years and these undoubtedly are of some benefit.

Sleet is another formidable foe to the successful operation of transmission lines in New England. Sleet destruction is caused at comparatively rare intervals, but the ensuing interruptions are of a major consequence on account of the inherent length of time necessary to repair the damage. The sleet storm of 1921 was more severe than any storm of established record in New England. This storm proved the inadequacy of off-set vertical lines and established the necessity of providing tower strength to insure against tower failure on important lines. We are attempting to design major lines to operate through the 1921 conditions with not more than broken conductors. Considerable use has been made of sleet thawing on lines that can be taken out of service.

CIRCUIT BREAKERS

It is perhaps of fundamental importance to avoid disturbance in so far as possible, however, the rapid removal of faults, once they occur, is a very important consideration and it is only recently that circuit breakers even approaching adequate speed have been secured. The Fifteen Mile Falls development was equipped with 220-kv. circuit breakers that will have an over-all relay and breaker time of the order of eight cycles (0.013 seconds) and it is hoped to secure similar characteristics in breakers to be purchased in the future for the lower voltage developments. Tests on the 220-kv. breakers, some of which were taken under actual operating conditions, showed the removal of short circuits in quite a spectacular fashion. Only very small voltage disturbances were caused and a remarkable lack of damage resulted at the point of application of the short circuit. Considerable increase in synchronizing power during short-circuit conditions between the Fifteen Mile Falls plant and the remainder of the system was also secured. It is our observation that the disturbances causing damage to circuit breakers have been very materially lessened in the past several years and it is thought that one of the largest factors has been the design of breakers of sufficient mechanical strength to be able to withstand gas explosions. However, considerable progress can be made in bettering the mechanical reliability of oil circuit breakers. It is imperative that oil circuit breakers be designed so that the possibility of their failing to open or to close be entirely avoided.

SYNCHRONOUS CONDENSERS

Our experience indicates that the economical operation of a high-tension interconnected system necessitates such power-factor correction as to assure the operation of the high-tension lines at practically unity power factor. Interconnected lines must also operate at somewhat less drop in potential to avoid voltage variation when the point of feed is shifted on the system. There is approximately 180,000 kva. of synchronous condenser capacity in operation on the New England Power System.

TRANSFORMATION

There appears to be little possible gain in attempting to improve the reliability or the efficiency of modern high-voltage transformers. We have come to look upon this piece of equipment as being as safe against disturbances as any other type of equipment in service.

There has been no occasion on the New England system to make use of load ratio control for shifting load nor balancing power between parallel circuits. There have, of course, been many occasions when it has been difficult to get the proper distribution of power, yet it has not been felt that any situation would justify the expense of load ratio control. The accurate regulation of system frequency together with the wide use of synchronous condensers has obviated to a considerable degree the need of phase shifting equipment. Existing conditions can easily change or new conditions arise so that we shall be forced into this expense.

TAP SHIFTING

Extensive use has been made for many years of arrangements whereby transformer taps can be changed readily and rapidly when the transformers are deenergized. Several of the intersystem ties have been made through transformations consisting of at least duplicate capacity equipped with ratio adjusters and it has been practical to change transformer taps one at a time during changes of load conditions. This method of operation has been so successful that the New England companies were among the first to standardize upon external tap shifting devices for practically all important transformers.

Discussion

For discussion of this paper see page 1280.

The Pennsylvania-Ohio-West Virginia Interconnection

BY HOWARD S. FITCH*
Associate, A. I. E. E.

***Synopsis.**—This paper describes a specific interconnected system wherein ten independent operating companies of western Pennsylvania, eastern Ohio, West Virginia, and Maryland operate normally in parallel to secure the manifold advantages of the interconnection of their facilities. Some of the benefits derived from the interconnection of these ten companies and the principles and methods followed in actual operation including very brief descriptions of physical plant are treated. The feasibility of coordinating the operations of an interconnected system through a working operating committee functioning in part through the joint dispatching organization of two of the companies without sacrificing independence of operation, is discussed.*

INTRODUCTION

MODERN power system management fully recognizes the importance of the linking of power sources, transmission facilities and load areas, whether these interconnections are ties between power systems independently owned and operated or connections between power sources and loads of a single system and ownership. Many papers on this subject describe the fundamental plan of power supply and the operating problems of interconnections of systems largely under one management, treating of a basic load area, a fundamental plan of power supply, and a developed method of operation.

The purpose of this paper is to describe the plan of interconnection and operation of contiguous power systems, independently serving a vast industrial region. Each system is under separate control, both financial and operating, with all the diverse standards and ideas of technical, commercial, and accounting nature. Each system has its own tale of romantic growth and progress from the small local generating plant to the highly developed load area with its network of power lines served by modern power stations.

It was inevitable that as each system grew, a mutual interest should develop between neighboring utilities in the planning of power supply extensions into the intermediate territory. It was proper that these neighboring independent companies should cooperate to realize any possible benefits to be derived through interconnection. It was natural that a common understanding of the every day problems of parallel operation should follow, this consensus of opinion being expressed by the Working Committee of operating men from each of the ten individual systems.

TERRITORY SERVED

Character of Territory. The territory served by the ten operating companies constituting this interconnected system has an approximate total area of 101,000 sq. mi. and a population of about 9,000,000 including 300 cities and towns. The metropolitan areas of Cleveland and Pittsburgh each have a population in excess of 1,250,000. Other cities of over 60,000 people are Akron, Toledo, Canton and Youngstown, Ohio; Erie, Altoona, and Johnstown, Pa.; Charleston and Huntington, W. Va. Industrial towns average from 5,000 to 25,000 people. A large part of the remainder of the population resides in 3,200 communities classed as rural,—less than 2,500 people. The character of territory served by these companies illustrates the recent trend toward decentralization of industry and population.

Nature of the Load. An estimate of the peak load of this group for 1930, occurring in December between 9 and 11 a. m. is 1,750,000 kw. The annual load factor is about 70 per cent.

Although 85 per cent of the consumers are domestic, 1,400,000, industry constitutes the bulk of the load. The industries served consist principally of bituminous coal mines and coking plants; sheet steel mills; electric steel melting and ore reduction furnaces; rubber goods and tire factories; glassware and plate glass plants; cement plants; refractory, brick, tile and porcelain works; and countless machine shops, foundries and small plants manufacturing mine, mill, railroad, and electrical equipment.

Electric railway systems under the same holding company management with the power companies which serve them, operate in Pittsburgh and Allegheny County, Pennsylvania, throughout the coal regions of southwestern Pennsylvania and northern West Virginia, and in Akron, Canton, and Massillon, Ohio.

CLASSIFICATION OF SERVICES—CONTRACTUAL RELATIONS

The contractual purposes of making interconnections according to the important benefits to be derived are represented on this combined system in their every essential; reliability of service, capital investment economies, operating economies, and the stabilization of frequency, voltage or reactive kilovolt ampere conditions and transmission systems. Typical examples are given of contractual relationships, the inception of which was due to one or more of these purposes.

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*Gen. Supt. of Substations, West Penn Power Co., Pittsburgh, Pa.

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TABLE 1—DATA ON GENERATOR RATING AND OUTPUT OF 10 INTERCONNECTED COMPANIES

System	Generator rating Dec. 31, 1929				Added capacity 1930 steam plants		Generator rating Dec. 31, 1930	Total 1929 kw.-hr. output
	Steam plants		Hydro plants					
	No.	Kw. rating	No.	Kw. rating	No.	Kw. rating		
Appalachian Electric Power Co	8	302,540	5	36,900		5,000	344,440	1,484,761,000
Associated Gas & Elec. System (West. Penna. Group)	8	89,175	2	48,200			137,375	491,037,034
Cleveland Electric Illuminating Co	4	447,000			1	150,000	597,000	1,447,103,594
Duquesne Light Co	3	384,000			1	60,000	444,000	1,573,445,327
Ohio Edison Co	4	279,000	1	2,175			281,175	1,018,759,180
Ohio Power Co	15	395,345	4	2,850			398,195	1,544,252,000
Ohio Public Service Co	8	130,100					130,100	611,482,217
Penn Central Light & Power Co	4	76,100	3	4,420			80,520	237,817,248
Toledo Edison Co	4	160,200	2	6,800			167,000	514,980,108
West Penn Electric Co	26	457,374	9	55,595			512,969	1,938,955,818
Total of all companies	84	2,720,834	26	156,940	2	215,000	3,092,774	10,862,692,526

Frontier Exchange. Neighboring companies first contacted on the frontiers of their respective systems and interconnected for the mutual protection of those districts having only one source of power. Such interconnection of transmission lines made it possible, without suspending the customers' service, to take a section of line out of service for repairs, especially at week-ends, thus eliminating the hazard of working on live lines and insuring the highest degree of maintenance. These lines were usually small in capacity and did not permit of continuous parallel operation. However, in 1916 the Duquesne Light Company of Pittsburgh and the West Penn Power Company of Western Pennsylvania, operating in territory immediately adjacent to each other, remained in parallel for 100 hours continuously over two connections of light capacity 22-kv. transmission lines. Although it was believed at this time that the extreme watchfulness essential to parallel operation did not warrant the continuance of parallel operation, nevertheless it was proven this early in the transmission history of these two systems that they could be paralleled for emergency purposes in case of failure of generating units or for the transfer of suitable blocks of load until the disabled system could regain its generating capacity.

Investment and Operating Economies. During the war period, 1916 and 1918, an exchange energy contract between the Duquesne Light Company and the West Penn Power Company necessitated the paralleling of these systems twice each day to transfer blocks of load. The peak load of the Duquesne system was greater in the evening than in the morning and the reverse condition prevailed on the West Penn System so that each company had a surplus of generating capacity at the time when the aggregate demand of the consumers of the other company was the greatest.

Beginning with June 1916 and continuing to the present day, energy has been exchanged to supply those fringe areas of each system, which are at a considerable distance from their respective generating stations, to the manifest advantage of both parties and of the service.

Dove-tailing Construction Programs. This early contract of 1916 also provided for the development of the respective systems of the Duquesne and the West Penn with such proper harmonious cooperation in the construction and operation of additional generating stations and additional substations that in the interests of both companies and of the public, avoidable expenditures would be prevented and the cost of supplying energy would be minimized. From the initial sale of 10,000 kw. by the Duquesne Light Company to the West Penn Power Company, 1916-1918, in which period the West Penn System was constructing its Springdale power station, there has been a total of four firm energy short-term contracts between these systems for the purpose of dove-tailing the steps in power station building programs. One of these contracts terminated August 31, 1930 shortly before the placing into operation of the James H. Reed power station of the Duquesne Light Company. In this manner on this interconnected system, economic waste that goes with building generating stations too far in advance of the individual system load has been eliminated by staggering construction between independent companies.

Combined Financing—Power Stations. An example of this type of interconnection is the Windsor power station jointly owned by the Ohio Power Company of the American Gas & Electric System and the West Penn Power Company. After considerable study in 1915, a site was located on the Ohio River, about 9 miles above Wheeling, W. Va., for a station to meet the increasing needs of the Ohio Power Company, as further expansion of its Canton plant was impossible due to lack of water, and to give a firm source of power to the West Penn Power Company in its western area, which was being fed by a long low-voltage transmission line from its Connellsville plant with considerable voltage and power losses. The joint Windsor station was then built in 1917 which in effect produced all the major benefits of the interconnection of generating facilities as well as many other operating and investment economies. This was the first time any arrangement of this kind had been made in the United States. It is also interesting that the Windsor station was the first station of this magnitude to be built at the mouth of coal mines and securing coal for fuel without the use of river or rail for transportation.

Although the contract for joint operation of the Windsor station provided that one company should operate the power station and the other company operate the coal mine and that these operations should alternate each year, so satisfactory have been the results of the joint operation that the Ohio Power Company has operated the power station since the beginning and through the increases of station capacity to its present rating of 185,000 kva. and the West Penn Power Company has operated the coal mine. Each company is particularly well fitted in its relation to Windsor to continue to perform that part of the work which it initiated and no request has ever been made by either company for a change in the authority of the respective operations.

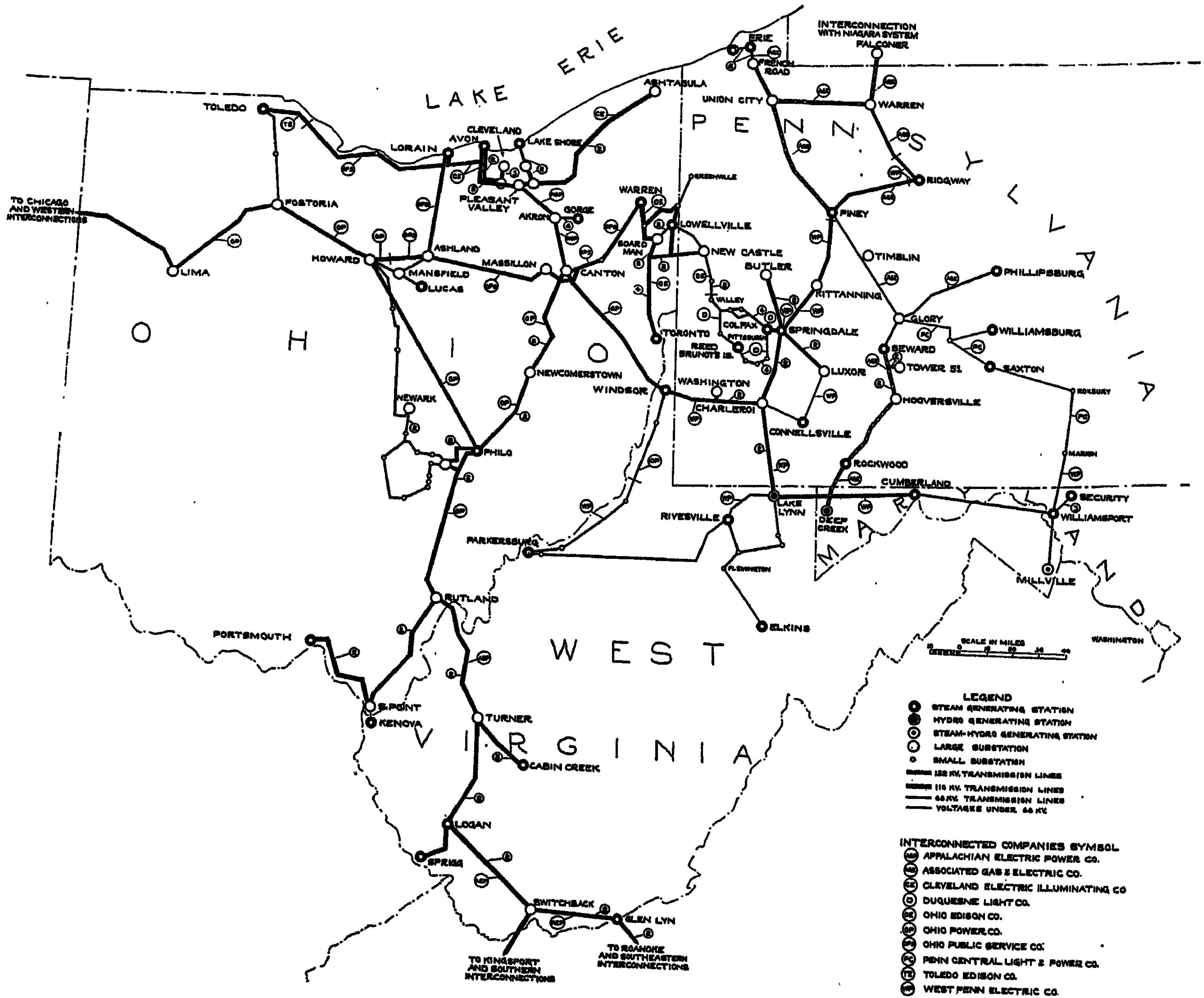

FIG. 1—THE TRANSMISSION BACKBONE OF THE PENNSYLVANIA- OHIO-WEST VIRGINIA INTERCONNECTION

Combined Financing—Transmission Lines. The interconnection between the Associated Gas & Electric System and the West Penn Power Company was caused by the desire of each company at about the same time to build high-voltage transmission lines, connecting its main properties to outlying properties served by old power stations. The Associated Company desired to build a transmission line between the Piney hydro station on its main system to the Warren station and the West Penn Power Company desired to build a transmission line from Kittanning on its main system to the Ridgway station. By collaborating, the West Penn Power Company built a line from Kittanning to the Piney hydro station and each company built sections of line between Piney, Ridgway, and Warren within its own territory, thus completing in 1926 an interconnection of all the desired properties and making possible the joint use of the same transmission facilities. Five very successful years of perfect cooperation have been a result of this unique arrangement.

Reduction in Spare Generating Capacity. Because of the strong transmission backbone throughout the interconnection, the whole system is in itself the best example of how planning can be done and operation accomplished safely with a much lower percentage in spare generating capacity than without such an interconnection. On this interconnection the emergency reserve capacities are spread over the various transmission systems that are interconnected, so that any one system will be called upon to furnish what, in many cases, represents only the overload capacities of the machines used in usual operation; all of which results in less capital invested in the individual properties and consequently a lower fixed charge to be absorbed by the output of each plant. In addition, therefore, to the more specific purposes of contractual relationship, this attractive advantage has weighed heavily in the consideration of interconnection made finally by several systems of the interconnected group.

Protection of Service. Of all the possibilities of interconnection, that of mutual assistance when assistance is necessary is commercially the most important. The ability to call on the resources of other power companies in addition to those owned, gives a feeling of great assurance to the man who is responsible for the continuity of service. Such an interconnection for continuous parallel operation was made when the 66-kv. Roxbury tie was built in 1926 between the Penn Central Light and Power Company and the Potomac Edison Company of the West Penn System. This interconnection has proven to be helpful in several instances of emergency at the Saxton or Williamsport power stations and on a number of occasions to serve consumers of the terminal substations or on the interconnecting line when a section of it was in trouble.

CLASSIFICATION OF SERVICES—OPERATING BENEFITS

Reserve Generating Capacity—Practise. The study of the problem of reduction in spare generating capacity on this interconnected transmission system has resolved itself into two phases. One is the utilization of the operating or spinning reserve capacity of the generating units and the other is the coordination of the operation of the reserve capacity between these various companies so as to carry the required spinning reserve in the most economical manner. The resultant diversity by combining spinning reserve capacities makes possible a decrease in the total reserve capacity in service without the loss of reliability, and the proper proportioning of the spinning reserve capacity between the component parts of the system decreases materially the amount carried on any one system. On this interconnected system it is believed that the spinning reserve carried by any one company should be 10 per cent of the load carried by a steam station and 5 per cent of the load carried by a hydro station. When any one company generates more than 20 per cent of its load on any one steam unit, it should carry a spinning reserve equivalent to 50 per cent of the load carried on this unit, as its proportion of the spinning reserve.

Each of the two large metropolitan systems, namely; the Cleveland Electric Illuminating Company and the Duquesne Light Company, serving respectively Cleveland and Pittsburgh and their adjacent territories, carries its own reserve which is equal to the largest unit on its system. These urban systems follow the practise of holding this reserve only in the overload and less efficient capacities of the generating equipment actually in operation. The tie lines from these two companies to the main interconnected system might not carry all the load placed upon them without damaging the cable, transforming, and regulating equipment in the event of the loss of the largest unit with insufficient reserve.

It is essential that member companies participating in the benefits of such a pool of spinning reserve capacity should be able to draw their requirements from the pool whenever an emergency arises on their system. It is therefore, necessary to have a means of determining what reserve actually exists in the pool to insure the existence of an adequate amount of reserve at all times. On this system Windsor, being the central point of the interconnected system, acts under supervision of the Working Committee as a clearing house for all data on existing reserve capacity. Each company relays to the Windsor load dispatcher, not later than 3:00 p. m. of each day its expected conditions with respect to load, capacity in operation, load to be carried by the largest unit and spinning reserve for the following day. A further report of these conditions is made not later than 6:00 a. m. the following day. Each company makes a frequent check of these conditions throughout the day to ascertain if its spinning reserve capacity is equal to or in excess of the requirements specified. The Windsor load dispatcher is notified at once of any condition which arises to change the status of the reserve from the expected condition previously reported.

It is also essential that the specified spinning reserve be maintained by each company, either by placing in operation idle capacity or by securing reserve capacity elsewhere. Should a condition arise which causes one company to draw on the pooled reserve or to reduce its proportion of reserve due to loss of capacity or excess load, the company notifies the Windsor dispatcher and makes arrangements to increase its proportion of the spinning reserve to that required as soon as possible. In no case is the spinning reserve deficient for more than two hours. The companies concerned in the reserve are notified at once of any condition which causes a deficiency of the spinning reserve. If an accumulation of circumstances causes the required spinning reserve to be decreased by more than 25 per cent, the Windsor dispatcher at once has a check made of all possible reserve and if the actual spinning reserve is not equal to at least 7½ per cent of the then total system peak, he requests that additional capacity be placed in service as soon as possible at the most convenient location.

All ten systems of the interconnected group furnish the Windsor dispatcher, not later than Friday of each week, information on their expected operating conditions for the following week. Any system desiring to make use of available spare capacity can find out from the Windsor dispatcher where this reserve may be secured. All negotiations for supplying spinning reserve capacity in this manner are made between the individual companies as a two-party agreement. Such an arrangement naturally leads to a schedule between the various systems for dove-tailing maintenance of large units and other contemplated work which may temporarily change operating conditions.

Perhaps the most outstanding two-party verbal reserve capacity agreement ever entered into in this country was made in September 1930, between the Duquesne Light Company and West Penn Power Company. The occasion for this unique arrangement to supply spinning reserve capacity arose when the navigable waters of the Monongahela River below Fairmont, W. Va. and as far down river as Brownsville, Pa., became so depleted by unprecedented and continual drought that the pools of this section were scarcely navigable. The government authorities were faced with the necessity of withdrawing what water remained in the upper pools to maintain navigation in the lower pools between Brownsville and Pittsburgh. Such an act would have affected the water supplies of a very large population in West Virginia and would have caused the cessation of mining operations by many mines loading to the river with all the attendant idleness of labor and tie-up of machinery. The losses of labor and the stand-by charges on equipment alone were estimated to be $1,000,000 per month for the mines affected. To relieve this urgency the West Penn Power Company offered all of its impounded waters in the Lake Lynn hydro development at no cost to the Federal government. However, in order that the West Penn Power Company might be able to fulfil its power contracts in case of emergency in the loss of large generating capacity, it became necessary to arrange for spinning reserve capacity to replace Lake Lynn hydro station. The Duquesne Light Company offered its help, thus making possible the gift of all water in Lake Lynn to the government and the use of 80 per cent before the drought was broken. Such energy as the Duquesne might furnish the West Penn, should such a contingency occur, was to be returned by the West Penn at a time when the Lake Lynn hydro station could again generate energy. The agreement for this stand-by reserve capacity of the Duquesne Light Company to the West Penn Power Company was a verbal one and although it was never used in this exigency the reserve capacity was continually available as was the means of transmitting it to the West Penn Power Company.

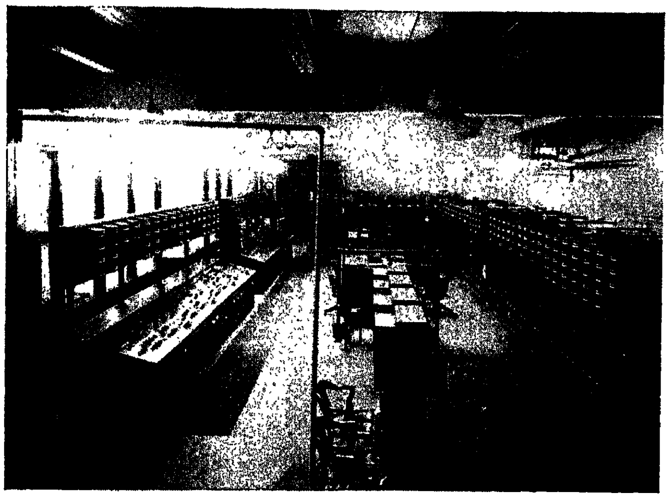
FIG. 2—VIEW OF SWITCHBOARD ROOM AND LOAD DISPATCHER'S HEADQUARTERS AT WINDSOR STATION

Reserve Generating Capacity—Performance. Troubles are encountered on this interconnected system the same as they are on any other system for apparatus, no matter how perfect, and plants, no matter how well designed, break down. Interconnection, however, has wrought wonders so that the public served is often unaware that trouble has ever occurred. According to the law of probabilities it would seem on an interconnected system that has 56 generators of 19,000 kw. capacity and over, that the probability of losing more than one generator at the same time would be more than a coincidence. Except those troubles due to instability, such cases are quite rare.

In November, 1927, unit No. 1 at the Philo station of the Ohio Power Company, 40,000 kw., developed internal trouble and was taken out of service for inspection and repairs.[2] Two weeks later, and before unit No. 1 was replaced on the line, unit No. 2 of the same capacity developed internal trouble also and was removed from service, thus completely shutting down the Philo station and reducing the capacity of the Ohio Power Company System by 80,000 kw. It was not possible to get unit No. 1 back in service. The accident to unit No. 2 was on a Saturday, when the load was light, so that the system did not feel the loss. But all day Monday and until noon Tuesday the interconnections, each adding their quota of help to the 30,000 kw. above normal supplied by the Cleveland Electric Illuminating Company, carried the interconnected system load of the Ohio Power Company without the slightest disturbance or hitch until one of the Philo units was returned to service.

The West Penn Power Company had a case of trouble in July 1927 at its Springdale station when unit No. 2 developed blading trouble and had to be removed from service. The switchboard operator pulled unit No. 1 off the line at the same time, as this turbine was hunting and he believed it also was in trouble. Springdale station capacity was thereby reduced 40,000 kw.,

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[2] For references see Bibliography.

5,000 kw. of which could be picked up on the remaining units in this station and the interconnected system picked up the remaining 35,000 kw. of this load. It took one hour for the West Penn System to bring capacity into service at its various plants during which period the interconnected system served all the load perfectly.

On February 11, 1931 at 8:06 p. m. one transformer, 16,667 kva., in Canton No. 1 bank failed at Windsor,—the joint station of the Ohio Power Company and the West Penn Power Company. Differential relays cleared transformer bank No. 1 from service. There are normally two banks operating in parallel, banks No. 1 and No. 3, and at the time of the failure of bank No. 1 each bank was carrying 45,000 kw. to the west. When bank No. 1 tripped the sudden overload on bank No. 3 tripped it out on overload relays thereby separating the eastern and western systems at Windsor. At Windsor 90,000 kw. to the west was dropped almost instantaneously and was absorbed by Philo, Cleveland and other western and southern stations, with a loss of frequency of only 0.17 cycle and no service disturbance. The frequency of Windsor and the eastern stations increased 0.35 cycle with no service disturbance. The eastern and western systems were paralleled at 8:09 or three minutes after the time of the initial trouble.

Load Diversity. When individual systems, now a part of this group, began to be interconnected some of the advantages that were obtained previously in the tying together of small communities within the same system were no longer obtainable. One of the things that disappeared, and very quickly, was the saving due to diversity. A typical case can be taken of the western part of the system on which with a system peak of 490,000 kw. the diversity between the four individual systems was only 15,000 kw. or 3 per cent.[2] In general, studies of other groups have given similar results.

As a large portion of the industrial load is coal mining, in which industry the working day is practically over at 4:00 p. m. it would seem that the factor of diversity could be used to advantage with respect to the lighting load of a metropolitan area, such as Pittsburgh. This has been somewhat true in the past, especially in December, but in the last two years the evening peak of the transmission groups, who are essentially industrial serving systems, has approached within 8 per cent of the morning peak. The mere elimination of normal expected hydro capacity in the evening due to low water conditions such as has prevailed since November 1929, creates an evening peak for the steam stations.

The industrial load is noticeably much more diversified within the last two years, no doubt due to the use by many industries of off-peak power,—4:00 p. m. to 7:00 a. m.,— especially electric furnaces and municipal water pumping stations. The economic desire of many manufacturers to operate at least a part of their plants during the entire 24-hour period coupled with the lower cost of off-peak energy in regard to demand rates for a highly fluctuating load is also probably responsible for this condition.

This interconnected group operates entirely on eastern standard time excepting Pittsburgh and adjacent towns which operate on daylight saving time during the summer and which departure from standard is scarcely noticeable to the group as a whole. The Western and Chicago Systems, operating on central time, affect the frequency regulating station at Windsor to give it two noon-hour variations each week day.

STABILITY

In the early history of parallel operation of generators and power plants on this interconnected system, instability was accepted as one of the many problems resulting from the attempt to keep the component parts of the system in parallel with weak transmission lines. With the installation of the 132-kv. transmission backbone and with more attention in the selection of proper equipment characteristics in the terminals of this system, instability ceased to be such a serious problem.

Windsor. As Windsor is the center of all interconnected operation so is this station the center of the stability problem. The eastern and western systems are here paralleled on the 11-kv. generating bus to which are connected the six generators and one synchronous condenser, each with a capacity of 30,000 kva. Between generators are reactances of 5 per cent., and as far as possible loads are taken off the bus sections to agree with generator outputs. The eastern system is principally connected to this bus through three banks of transformers totaling 86,000 kva. and the western system solely through two banks of transformers totaling 100,000 kva. All banks are fixed ratio and transform to the 132-kv. system with about 10 per cent reactance. An emergency tie between the 132-kv. systems is provided.

The generators at Windsor are of the large air gap type which requires a heavy no-load magnetization. Consequently a low maximum voltage is indicated with full excitation and no-load. These machines are not much affected by load changes, have a high short-circuit ratio and are inherently stable. The voltage regulators at Windsor are of the Tirrill type, one per exciter which is direct connected to its generator. This arrangement of exciters is satisfactory from the point of view of stability, since steam units do not overspeed to any great extent. The voltage regulators operate in parallel through the usual compensating coils which force a correct sharing of the reactive kva. Automatic frequency control operates normally upon three units.

Throughout its history the Windsor station has stood like a rock against the many momentary surges transmitted to it from the east or the west. It has successfully handled many rapid changes of load in the order of 50,000 to 90,000 kw. The problem of stability on each system is mainly of staying in synchronism with Windsor.

Eastern System. To the east of Windsor station there are the Springdale steam and the Lake Lynn hydro stations of the West Penn System joined together at the Charleroi transmission substation which is distant 41 miles from Windsor, 31 from Springdale and 29 from Lake Lynn. From the Springdale station radiate the connections to the Duquesne Light Company-Colfax, Reed and Brunot Island stations,—and to the Associated Gas and Electric System—Seward, Erie, Piney and Deep Creek stations. From the Lake Lynn station radiate the West Virginia connections—Rivesville and Parkersburg stations, and the Western Maryland connections—Williamsport and Cumberland stations, both of the West Penn System, and from Williamsport the connection to the Penn Central Light and Power Company, Saxton station. The synchronizing power of the lines between Windsor and Springdale and between Windsor and Lake Lynn is 500,000 kw. which is ample to hold these stations together.

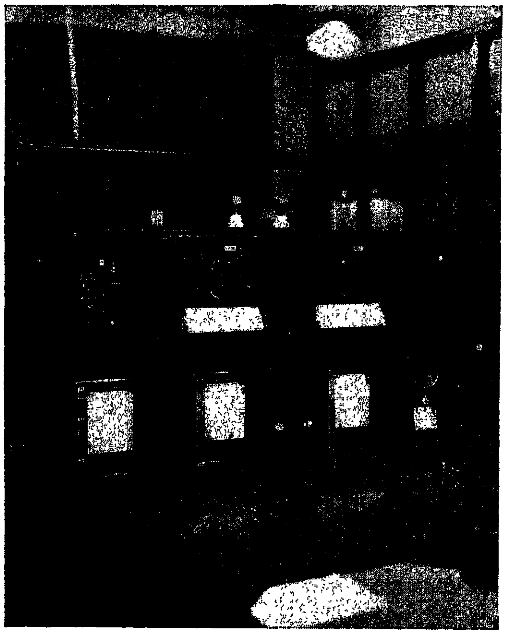

Fig. 3a—Front View of Automatic Frequency Control Panel at Windsor Station with Recording Charts of Frequency, Time, and Loads of Tie Lines to Eastern and Western Connections—All Located Adjacent to Switchboard Operator's Desk

The Lake Lynn hydro station and the Springdale steam station generate at 11.2 kv. and each step-up through transformers of about 10 per cent reactance to a 132-kv. bus. The generating units at both stations have very high no-load full excitation voltages—17.5 kv. and consequently a low short-circuit ratio.

There is an unusual situation with respect to the Piney tie between the West Penn System and the Associated Gas and Electric System which is made through three 5,000-kva. auto-transformers 132-110 kv. with dead-grounded neutral. Thus either system may receive ground fault disturbances from the other system. A similar installation is made at Cumberland where auto-transformers 132-66 kv. are installed. So far no difficulty has been encountered from these connections.

The connection between the Springdale and Colfax stations is made through a transformer bank consisting of three 12,000-kva. single-phase units connected delta-delta 132-66 kv. and an auto-transformer bank, three-phase core type 36,000 kva. 66 kv. Y, 72.6 kv. Y.[3] This auto-transformer is equipped with load ratio control making it possible to obtain 10 per cent buck or 10 per cent boost in voltage without removing the transformer from service. Over a wide voltage range, these systems thus have a means of regulating the wattless current flowing between them.

The most vulnerable point of this eastern system is near the Springdale station where there is a short-circuit capacity of 1,200,000 kva. Calculations indicate that a three-phase short-circuit fault must be isolated within 16 cycles or the units are likely to go out of step. On March 21, 1929 at 4:15 p. m. there occurred a case of dynamic generator instability when a fault occurred on both of the two 132-kv. lines toward Luxor substation at a point three miles from Springdale. During the fault the two 25,000-kva. generators tripped out on the steam end upon overspeed and one of the 35,300-kva. generators was removed from service by the operators, as it was thought to be surging. Only one 35,300-kva. generator was left in operation and 96,000 kw. of load was dropped at Springdale. Of this amount Windsor picked up 55,000 kw. The duration of the fault was three minutes and the 25,000-volt buses at the adjacent transmission substations were reduced to about one-half voltage. However, at Lake Lynn and Rivesville

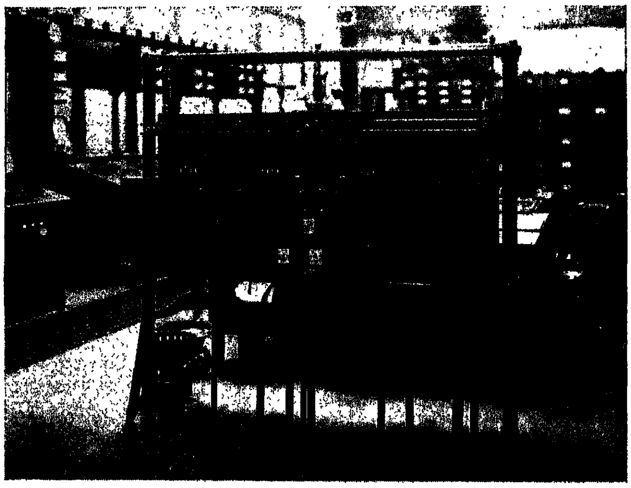

Fig. 3b—Rear View of Automatic Frequency Control Panel at Windsor Station Showing Spring Mounting to Eliminate Vibration

stations there was only a momentary 20 per cent drop in voltage.

As a result of the above case of instability due to ground faults, short circuit and line clearing, with attendant changes in loads and load power factors, the excess voltage protective devices of the voltage regulators at Springdale were removed from service. The wisdom of this procedure was borne out when a more severe short circuit occurred on December 23, 1929 near the Springdale 132-kv. bus and no generators tripped out of service.

The power factor at Springdale is high, it being difficult to average lower than 95 per cent on the five generators, which have low short-circuit ratio characteristics. In several instances one of the generators has fallen out of step due to the operators placing a leading power factor upon it during load shifting. No interruption or disturbance to service was involved in any case.

Improving the governor action is a problem upon which the operating engineers of the Duquesne Light Company have done much experimental work including load dumping tests.[4] Modifications in the apparatus have resulted in a much faster and more accurate following of the speed changes, allowing the governors to hold the turbines below the limit of the auto-stop setting. The governors of this system are, therefore, probably more responsive to sudden load changes than those of any other operating group on this interconnected system. Nevertheless tests have proven that the period of the governor oscillation and the load oscillation on the generators do not have a time phase that would sustain a surge and that the governors are sensitive enough to hold the turbine from overspeeding and tend to check the speed of the turbine during a pole slip.

Western System. To the west of Windsor Station there are the Philo Station of the Ohio Power Company, Toronto Station of the Ohio Edison Company and the three stations; Avon, Lake Shore, and Ashtabula of the Cleveland Electric Illuminating Company. These are joined together at the Canton transmission substation of the Ohio Power Company, this being distant 55 miles from Windsor, 73 miles from Philo, 102 miles from Toronto and 28 miles from the Pleasant Valley substation, which in turn joins the three generating stations of the Cleveland Electric Illuminating Company. From the Philo Station radiate toward the south the connections to the Appalachian Electric Power Company, Cabin Creek, Kenova and Glen Lynn Stations, which in turn interconnect with the Carolina Power and Light Company at the Virginia-North Carolina state line near Danville, Virginia. Also from the Philo Station toward the west radiate the connections to the Howard, Lima and Fort Wayne, Indiana transmission substations, the Twin Branch steam station and the Chicago interconnected systems.

The Philo and Toronto steam stations generate at 11 kv. and each steps up through transformers of about 9 per cent reactance to a 132-kv. bus. Recent oil circuit breaker tests at Philo developed a short-circuit capacity of 1,735,000 kva. on the 132-kv. system at Philo.[6]

From the Canton Substation extends a line through the Alliance Substation of the Ohio Public Service Company and the Boardman Substation of the Ohio Edison Company to the Valley Substation of the Duquesne Light Company. Also from the Canton Substation extends the connection to the Windsor Station, to the Charleroi Substation and Springdale steam station of the West Penn, to Colfax steam station and Valley Substation of the Duquesne Light Company. These two lines form a 250-mile high-tension transmission ring involving five power companies and a total generator capacity of nearly 1,250,000 kw. Occasional operating with this ring closed on itself has demonstrated the inflexibility of interchange control and therefore, the loop is left open at the Valley Substation. A measured angle exists at 19.6 degrees which corresponds to a calculated angle of 17 degrees described in an A. I. E. E. paper.[5]

Comparatively few actual cases of static instability have been reported on this interconnected system. An A. I. E. E. paper of January 1931[6] describes a case which occurred on the Appalachian Electric Power Company's system at Kingsport, Tennessee, where a comparatively weak interconnection is made with the Carolina Power and Light Company. A disturbance occurred on the Carolina system resulting in a burden on the interconnection in excess of the static stability limit of the lines involved with the result that the two systems pulled entirely apart and the voltage at Kingsport dropped practically to zero in approximately two seconds as recorded by high-speed instruments. Subsequent tests using instantaneous relays showed a power swing to 80,000 kw. which checked with approximate calculations of the stability limit for these interconnections.

Reactive Component Flow Control and Voltage

The regulation of the flow of reactive power and the distribution among generating units is not a problem of this interconnected system due to the high power factor maintained on lines and generating stations. This is partially due to the character of the load with a large amount of synchronous equipment but in the main due to the synchronous condenser capacity located at the transmission substations. The West Penn Power Company has 63,500 kva. in eleven synchronous condensers located at ten transmission substations. The Ohio Power Company has 85,000 kva. in synchronous condenser capacity located at its various transmission substations. If the capacity of the spare generator at Windsor, operating as a synchronous condenser, giving about 80 per cent of its rating, or 24,000 kva. leading is added, there is a total capacity of synchronous condenser equipment alone of 172,500 kva. in these two systems not including the generating units at hydro stations which may be operating with low gate opening.

The voltage of the generating units at the principal power stations is held practically flat, there being not more than a 3 per cent variation between light load and heavy load. By means of the synchronous condensers the voltage at the transmission substations is held to less than 2 per cent variation.

POWER FLOW CONTROL AND FREQUENCY

Close regulation of the load among the interconnected systems of this group and among the individual power stations of each system has been a most difficult problem. As each system joined the interconnected group it would have to scrap, in many instances, much of the operating practise of load and frequency regulation it had built up over a long period of operating experience. The Working Committee of operating executives has held many meetings, in which these problems have been analyzed by all and a common basis for action determined. These meetings have been followed by continual educational work among the load dispatchers and switchboard operators until satisfactory operation was accomplished. From the very beginning all operating men were in accord that the interconnection must work and that it was their job to make it work. The sacrifice of personal opinions and private practises and the desire to do whatever was best for the common good have resulted in notable progress being made.

It was recognized early in the history of this interconnected system that in the problem of plant loading or tie line control and in fulfilling the essential terms of the many contracts through which each system interconnected with its neighbors, that frequency control was a matter of vital consequence. As early as 1924 the operating executives agreed, after there had been much confusion and continual bickering between the operators on shifts, that the frequency as recorded at Windsor Station whether it was correct or not, would be the standard system frequency. Windsor station was then equipped with duplicate sets of the latest type of frequency recorder and the usual frequency or time clocks.

Those companies which were interconnected with more than one other company and at different points, were greatly limited in their ability to maintain correct loading on the various interconnecting tie lines. While it was not difficult for a company to maintain the load on its tie lines between its stations, or between its system and the central frequency control regulating station, it was difficult for those companies interconnected to it and still farther away from the center of frequency control to regulate the amount of power flowing in the interconnecting tie line.

For instance, one company would regulate the flow of power from its station by opening and closing the turbine governors, which would tend to change the system frequency.[7] Such a change being made at the first station without the knowledge of the frequency regulating station would result in a variation of the frequency before it was caught. The frequency adjusting station would then observe the change in frequency and pick up or drop load to bring the frequency back to normal. These variations would cause the load to change on other turbines having sensitive governor adjustments all over the interconnected system, and numerous adjustments would have to be made before the proper divisions of load were restored. High frequency often resulted, especially during light load periods. On the other hand, during periods of very heavy load or when the steam pressure became low at one station, the operators would shake off load to relieve the overloaded condition of their station and periods of low frequency would occur. It was usually 9:00 a. m. before the system settled down to the morning load which steady condition would last until 11:45 a. m.

This kind of operation was very unsatisfactory and often created peaks between the different companies, which were difficult to explain and to adjust when the billing was being discussed. It was believed by the working committee that if the frequency could be held at 60 cycles, with but a very slight deviation—less than 1/20 cycle,—the outlying companies would need only to adjust the load on their interconnecting tie lines, the next company in turn adjust its tie line load and so on to the last tie line connecting to the central frequency regulating station. In this manner the tie line load equilibrium would not be disturbed.

Windsor Station, being the center of all other operating features, was assigned the task of holding a flat frequency with six 30,000-kw. generators in the early part of 1929. As no automatic frequency control system had been installed, one operator on each shift was assigned practically the sole duty of holding a steady frequency by adjustment of the six governors. This was a radical departure from all previous practise for heretofore load had been picked up or dropped at Windsor by simply adjusting the governors as long as the frequency was not unduly altered. Now Windsor operators were to be more watchful over frequency and more agile in adjusting it than the other operators of the system had been and were to concentrate not on loading the station but on maintaining a close frequency range, whereas all other operators were to concentrate on maintaining a close tie line load adjustment and forget frequency.

This new scheme of operation worked successfully from the start. Troubles with tie line regulation seemed to disappear like magic. Whereas it had been the usual practise to adjust tie lines three or four times an hour, now three or four times a morning or afternoon or evening suffices.

In May 1929 an exhibition sample of an automatic frequency control device was temporarily installed at Windsor, thus relieving the shift operator of his onerous duties. This equipment had an over-all adjustment of two cycles plus or minus 60. Permanent equipment in duplicate was then ordered and installed early in 1930 with an adjustment range of 0.25 cycle plus or minus 60. Although this equipment was installed to control all six generators, it was found in normal operation that three or four generators would adequately hold the system frequency within 1/40 of a cycle plus or minus 60.

After a year's study of frequency regulation by one station only namely, Windsor, during which period several other large interconnected systems were added and the control of their frequency also taken over by Windsor, it was found that the only real difficulty of this scheme of regulation occurred at the rapidly load shifting periods of the day, as 7:00 a. m., noon hour, and 6:00 p. m. At these periods it was not unusual for the load on the Windsor station to shift from 60,000 to 90,000 kw. in 8 or 10 minutes. Although the boiler room operating forces at Windsor Station handled these radical changes in load in a most splendid manner, rarely ever popping the boilers or losing steam pressure, it was believed by the working committee that the installation of several other frequency control sets on this interconnected system would materially alleviate the conditions at Windsor. At the time this paper was written (March 1931) automatic frequency control equipment was being installed by two manufacturers for trial at the Windsor, Philo, and Springdale stations. The methods of operating under these new conditions have not yet been determined and positive results cannot be foretold. Preliminary tests would indicate that the objective had been achieved.

With very close frequency adjustment it has been possible to maintain electric time with a maximum error of not more than four seconds fast to four seconds slow in each month and with an average error when checking twice each day with Arlington of considerably less than one second. An inconvenience in operation due to this close time keeping operation results when the systems are separated for repair work on the tie lines or from fault reasons, for when the systems are paralleled the clocks on each system must correspond to the second or the connection must be broken again to adjust the frequency and consequently the time until the clocks do correspond.

COMMUNICATION AND TELEMETERING

In recent years considerable attention has been directed toward those situations which have arisen in the communication field as the result of the rapid growth in power output, the increased transmission line mileage, and more particularly the extensive interconnections. The requirements brought about by the vastly improved services rendered by the power utilities have necessitated the seeking of more adequate communication facilities. The problems in this special field require every facility of communication to the end that the most economical and serviceable systems may be made available. One answer to this problem now being used by several power companies of the interconnected system is the unification of private telephone services with the Bell Telephone System. Agreements have been entered into which provide for the termination of both privately owned circuits and leased circuits with suitable protection in the same private branch exchange switchboard where such a connection affords the most desirable arrangement.

The unified service plan makes possible circuits of proper transmission characteristics including the necessary freedom from noise. On power system communication lines the noise difficulty has been combated by using voice currents which tend to over-ride the induced currents to such an extent as to be intelligible. There is a limit, however, as to what can be accomplished along the line of high powered transmitters without the use of costly vacuum tube amplifiers. Transmitters using large currents have short life and high maintenance costs. By utilizing the lines of the telephone company for the long jumps and the lines of the power company for radial short distance communication service, a circuit is obtained which is not noisy and which is highly efficient.

Another method employed on this interconnected system for providing essential communication between power stations, load centers, and dispatchers is the carrier current telephone. The use of this system of communication has reached the highest stage of the art on the American Gas & Electric Company System, of which the Ohio Power Company and Appalachian Electric Power Company are members.[8] In July 1921 the Ohio Power Company conducted tests on the Windsor-Canton 132-kv. line which was the first successful communication over high-tension power lines of such a high voltage in the history of the art. The unique use of a common frequency by two independent operating companies for intercommunication has been carried out in territory around Canton, Ohio. A frequency of 90 kc. is used as a common frequency between the systems of the Ohio Power Company and that of the Ohio Public Service Company. The Ohio Power Company stations at Canton and Shelby are able to communicate with the Ohio Public Service Company station at Massillon over the common intersystem channel between these three stations.

One of the special services, to which reference should be made and part of the work of communication of a large interconnected system is that of distance metering. Such a scheme is in use between the Windsor Power station, Charleroi Load Dispatching headquarters and the Lake Lynn Hydro Station of the West Penn Power Company, a total distance of 75 miles, utilizing the telephone wires on the 132-kv. tower line structures to transmit the total load of the Windsor Power Station to the West Penn System to the load dispatchers and the hydro station.[9] Another use made of telemetering is to transmit the load taken by the Ridgway division of the West Penn Power Company to the Piney hydro station of the Associated Gas & Electric System, which enables the latter system to control correctly the flow in the interconnection between these companies and which interchange is involved with the use of the joint use facilities.

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Discussion

For discussion of this paper see page 1280.

Interconnection Development and Operation

BY G. M. KEENAN*

Fellow, A. I. E. E.

***Synopsis.**—The possibilities of interconnection can only be realized when the system is effectively developed and operated.*

The interconnected system functions as a unit but the companies owning the different parts have diverse interests which must be sufficiently coordinated both in development and operation to make the benefits of the interconnection available to all the participants. There is question as to how much coordination is sufficient.

The differences which exist between an interconnected system and a similar system under one ownership result either from the larger size of the interconnected system or from the variations in interests of the ownerships involved.

Interconnection development usually tends to reduce generation costs while increasing transmission costs and hazards. Possibly there are some limits to the size of the interconnected system and the degree of coordination desirable between ownerships. Closed loop operation involving several companies requires attention.

Interconnections may be operated by centralized direction or by cooperative methods between adjoining system operators. The unit characteristics of the system require some coordination of the group as a whole. Operation should be simplified as far as possible with adequate operating facilities.

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INTERCONNECTION is only one of the many factors contributing to the accomplishment of the purpose of the electric utility industry. The industry endeavors to provide the customer an electric supply, adequate in quantity, quality, and reliability for his requirements, at the place and time he wants it and at the minimum cost commensurate with a sufficiently encouraging return to obtain the men and money needed in the service. As far as practicable, natural resources are conserved and the development of the electric supply system is harmonized with public irrigation, navigation, flood control, and water supply projects. Justified interconnections contribute their bit only when effectively developed and operated.

Mr. Bauhan's paper on Interconnection Services defines interconnection, delineates and classifies its uses and indicates the procedure in evaluating a proposed interconnection. This paper attempts to outline methods used and problems encountered in interconnected system development and operation.

Synchronized operation of adjoining electric utilities has become such an established fact that no other type of interconnection will be considered here.

DISTINGUISHING CHARACTERISTIC OF INTERCONNECTION

The synchronized electric supply system functions as a unit, all the component parts responding to variations in the demands made upon it. This inherent unit characteristic is naturally recognized under the single interest of one ownership.

The interconnected system is a synchronized system, but the parts of it are owned by different companies, each of which must look out for its own interests. The unit characteristic must, therefore, be seen through a screen of diverse interests, and naturally is not as well defined nor as readily recognized as under one ownership.

The distinguishing characteristic of interconnection is coordination of the efforts of a group of independent ownerships in the development and operation of a unified electric system.

How much coordination is required? Some believe all the benefits of interconnection can only be obtained by developing and operating the system just as though it were all owned by one company; that the trend in that direction is inevitable; and that the individual company's interests need not be submerged. Others believe all the practical benefits can be obtained with much less coordination; that continuing interconnection over greater and greater areas so complicates complete coordinating arrangements as to make them economically unjustified; and that greater results will be obtained by maintaining stronger company individuality.

It is generally agreed that there must be at least sufficient coordination to care for equities in established contracts and to avoid penalizing any of the participating companies. Any additional coordination economically justifiable from the point of view of all the interests involved is equally acceptable.

DEVELOPMENT OF INTERCONNECTED SYSTEMS

There are two outstanding questions in interconnection development. How far is the enlargement of the interconnected system justified? Shall power flow in closed loops be controlled by means of special equipment or shall the power be allowed to flow as it would under one ownership and the equities of each company be cared for by net billing of the algebraic sum of the power flow on all of its connections into the loop?

Other engineering problems involved in the development of the interconnected system are essentially those of a similar system under one ownership. However, since few independently owned systems develop to the size of the moderate interconnected system, it may be appropriate to outline some of the problems and possibilities which have arisen.

Generation. Reduced capital and operating costs of generation usually result from interconnection. The development problem is so to take advantage of all of these possibilities as to achieve minimum total cost

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*Supt. Pennsylvania-New Jersey Interconnection, Hazleton, Pa.

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with maximum reliability in the total generating capacity of the system. Economically balanced distribution of capacity among the various types of steam stations and hydro stations, properly correlated for the absorption of all available by-product power from irrigation, navigation, flood control, water supply, and industrial developments is an intricate problem new in the breadth of its scope and possibilities. Heavy transmission for interconnection purposes at times justifies development of generating station sites otherwise unavailable due to transmission costs.

The trend in steam generating stations has been toward the largest unit which will economically fit into the system with practically no reserve provided in the individual stations. However, there are inviting possibilities in considering the transmission network as the bus and strategically locating large economical units in relatively small stations close to the load.

The flatter generating station load curve resulting from all types of diversity offers opportunities for the use of more economical vapor cycles not flexible enough to meet the demands of smaller systems. The station however, must be sufficiently flexible to meet the responsibilities imposed upon it by the variations in the hydro and by-product power.

The large peaks and proportionately large steam capacities of interconnected systems justify water power developments which could not be absorbed by smaller systems. The load characteristics of the system combined with the diversities in the flow of different streams and the increased quantities of low cost power available at off peak periods appreciably affect the justification and design of pumped storage and all other types of hydro stations. The design is further affected by the possibilities of using the generators as synchronous condensers and automatic stand-by capacity.

Transmission. Interconnection usually increases both capital and operating costs of transmission by increasing the quantity of transmission, the capacity of the units and the reliability requirements. This increase as a rule is partially offset but rarely equalled by the decrease produced in the internal transmission costs of the individual companies.

The transmission development problem is to discover means of reducing costs while providing an adequate reliable transmission network from the generator to the distribution system. Possibly these means of reducing cost do not exist in available equipment but can only be found in some entirely new development such as high-voltage direct-current transmission.

Interconnection tends to increase the transmission hazards to which each company is subjected by increasing the exposure due to the increased mileage of transmission lines tied together, by increasing the number of equipment units subject to inherent failures, and by increasing the current demands on equipment. The problem in development is to minimize the number of faults resulting from these hazards and the effect of the faults on the service.

Units of transmission and generation are going to fail even with faults from hazards reduced and adequate localization accomplished. At times such failures are going to separate sections of the system. The design therefore, must permit prompt resynchronizing. When the section separated from the system does not have adequate capacity to carry its load the set-up should be sufficiently flexible to drop the required quantity of load quickly.

The mechanical behavior at the point of support of the large conductors on high capacity long distance transmission lines is not well enough understood. Some scattered studies and tests are being carried on but a broad coordinated scientific attack is needed first to establish what is actually taking place at the point of support of these conductors, and second to devise methods of support to handle satisfactorily the actual conditions.

Much has been done to analyze and control short-circuit current, stability, voltage regulation, and power flow in closed loops, but with the increasing size of synchronized systems the problems are becoming both more important and more difficult of solution. Closed loops are developing rapidly and in some cases are hundreds of miles in circumference, involving many ownerships. Some general coordination of development is essential if the ownerships involved in these loops are to continue to get the benefits which justified their individual interconnections.

The development of the synchronized transmission system would be greatly simplified, the cost reduced, and operation improved by standardization of transmission voltages and phase relations.

System Operating Facilities. Planning, engineering, and operating groups cooperatively develop the system operating facilities necessary to indicate at all times the performance of the system and the adjustments required. As nearly as may be, controlling information on system performance is transmitted directly from the point at which it is observed to the point where compensating adjustment must be made. A fundamental communication and control plan should be developed, economically utilizing as required one or more of the following types of equipment: telemeters, teletypes, telecords, pneumatic tubes, open-wire telephone, cable telephone, carrier-current telephone, radio, remote control, supervisory control, automatic frequency control, automatic load regulation, and dispatching boards.

Experience seems to indicate that the communication and control system is rarely planned with the breadth of scope, the unity of purpose, and the economical utilization of available elements which the importance of operation justifies. Consolidation and correlation of guiding information are expedited by totalizing metering, and by system diagram boards both automatically and manually controlled which portray what is occurring, establish the status of the elements in the system, and indicate necessary adjustments.

An ideally regulated interconnected system would economically and promptly distribute load variations over all generating equipment in operation. Instantaneous consolidation and centralization of complete load information seems at present economically impractical. Something other than load therefore, must be used as the guiding factor. The automatic distribution of the necessary load control impulses to all generating stations to cause them to share the variations in load is possible but has not been used. It seems probable however, that refined frequency indication offers a guide to the variations required of generating equipment.

A standard frequency of great accuracy can be made available at all generating stations. Since the actual interconnected system frequency will be the same at all points, a measure of the divergence of this actual from the standard frequency offers a means of instantaneously and simultaneously adjusting generation at all stations to meet load variations. The problem has not been solved however, and a complete analysis is needed of the functions and the relations of steam turbine and hydraulic turbine governors, over-speed stops, automatic frequency and load regulators, and all other factors.

Metering. The metering equipment used in billing interconnection power requires more rational treatment than it has received in the past. Complicated, expensive, and yet inadequate metering has frequently resulted from attempts to predict definitely and to provide exactly for all theoretical equities. Actual operation has usually indicated a dearth of operating meters and an excess of billing meters.

Flexible transmission busing and switching arrangements almost invariably force the metering equipment onto the high-tension circuit. Equipment at these high voltages is a relatively new development about which much additional information is necessary. Both the voltage and the newness of the development make the equipment expensive and apparatus should be developed to accomplish the desired result at reduced cost.

INTERCONNECTION OPERATION

Objective of Operation. The objective of electric supply system operation is to produce most economically the most reliable service possible with the system provided while efficiently accomplishing maintenance. The coordination of the performance of all of the operating and maintenance personnel and operating equipment on the system to accomplish this objective requires planning and execution. The planning necessitates a forecast of the load demands and maintenance requirements and the establishment of a schedule of the activities to meet these demands and requirements economically. The execution of the plan requires coordination of load demands, maintenance requirements, personnel, and equipment to meet the schedule with such adjustments as are necessary in actual performance.

Interconnected system operation differs from system operation under single ownership only in the method by which the objective is accomplished, and in the necessity for properly taking care of the equities resulting from differences in ownership.

Since little has been written on the planning and execution of system operation it may be appropriate to review briefly the manner in which this is usually handled on a system under one ownership realizing that centralized interconnection operation follows practically the same procedure.

Planning Operation. Centralized system operation is the universal practise under one ownership.

Predictions are usually made of the monthly average and peak load demands and the maintenance requirements as far in advance as necessary. A guiding annual schedule for major maintenance is then prepared. It is assumed that arrangements have been made for adequate installed capacity or for purchased capacity to care for the maximum annual demand. It is recognized that daily maintenance requirements and variations from annual predictions on load demands must be taken care of by more detailed estimates and schedules prepared monthly and weekly and adjusted daily and even hourly.

Weekly forecasts usually prepared on Thursday or Friday for the following seven days are based upon a detailed study of load requirements and up-to-date information on daily maintenance work. The shape of the load curve at periods of rise and fall and at peak and valley periods of less than one hour duration must be known. The height as well as the contour of the system load curve must be established as accurately as possible. This total system load and maintenance information must then be broken down into load areas.

With this predicted load demand and maintenance requirement information, generating equipment is provided to protect against hazards and provide continuous service not only for the system as a whole but for each of the load areas. Knowledge of the characteristics of operating response of all of the equipment on the system to varying types of normal and emergency conditions is required.

Generators, frequency changers, and synchronous condensers and the loads on them must be scheduled to produce the lowest total production cost while utilizing all of the hydro and by-product power available up to the point where the cost of this power delivered exceeds the cost of other power. Knowledge of by-product and dump hydro power which is going to be available and of the factors entering into the cost of power delivered at any given point on the system is necessary. Cost of maintenance work at different periods must be balanced against the increased operating cost it necessitates.

Available hydro must be predicted based upon the factors entering into the run of stream hydro, pumped, and natural storage hydro, and hydro available from irrigation, navigation, flood control, and water supply developments. Information is necessary on probable weather conditions, ground water, snow on ground, rainfall over water sheds, long time predictions of rainfall and all of the other factors that enter into regulation of water power. Where there is more than one ownership involved in a water power development the utilization should be coordinated.

Complete and accurate starting and stopping costs, no load running costs and instantaneous incremental fuel and maintenance costs must be available on all fuel stations. It is important here to stress the difference between the incremental cost referred to for estimating purposes in Mr. Bauhan's paper and the instantaneous incremental cost necessary in scheduling operation. Cost of labor and supplies in generating stations are so nearly fixed that except in special cases where stations can be shut down for long periods they are not usually included. Methods of arriving at incremental costs and using them to get most economical system loading have been described in the technical press.

Costs at the generating station when considered in scheduling load distribution must be properly compensated for transmission losses.

The loading schedules arrived at in this manner must be continuously studied in relation to the corresponding actual results and the necessary adjustments and improvements made. Operation planning has not always received the attention it deserves. Methods of load forecasting require improvement for greater accuracy. Additional knowledge is needed on practically all of the factors entering into prediction of available hydro especially where large storage and complete regulation of stream flow is possible. Thorough coordination is needed with industrial and public developments having by-product power available.

Methods of establishing instantaneous fuel increment costs on running machines, starting and stopping costs, and no load running costs are well developed but much better basic test information is needed on many systems. The maintenance element of instantaneous incremental cost is influenced by many factors which are not capable of correct quantitative analysis as a function of load. Some studies have indicated that the ratio of fuel plus maintenance increment costs to fuel increment costs alone may vary under different assumptions from 1.05 to 1.45.

No exact method exists for conveniently determining the effect of transmission losses under operating conditions on the cost of the power delivered.

The method of developing the most economical load schedule from all these data needs considerable analysis and study.

Planning on Interconnected System. Planning operation on the interconnected system where centralized direction has been established follows practically the procedure outlined, but each ownership is responsible for providing all the required information from its system in such form that it may be easily coordinated into an interconnected system picture. Due to the size and expanse of the system, the problem becomes correspondingly complicated. For example, how much operating reserve does such a large system need, how shall this reserve be apportioned between the ownerships and how shall those ownerships not carrying their proportionate share compensate the companies who are sustaining them?

When centralized direction has not been established each company carries through its own planning as outlined and then checks with adjoining companies. Knowing the costs of the blocks of generation above and below that sufficient to carry its own load each company determines with its neighbor where load and reserve can be placed most economically.

Executing the Operating Plan. Execution of the operating plan under one ownership is invariably directed by a central position variously called system operator, load dispatcher, power director, and so on. System operator will be the name applied to the position directing the operation of the individual company, and local system operator will be the name applied to the sub-centers on the individual companies. The local system operator takes coordinating direction from the system operator.

The system operator keeps in touch with the demands made upon the system and the performance of the personnel and equipment in meeting those demands. His course is charted by the schedule of operation which has been prepared. He relates the demands as they develop to the predicted demands and from his thorough knowledge of all of the elements on the system, adjusts the performance of equipment and personnel most economically and effectively to compensate for deviations of the actual from the schedule demand.

The details of directing are so numerous it is essential to develop a method of procedure which delegates detailed observation of indications and responsibility for compensating adjustments as far down the line as possible, superimposing direction only where coordination is necessary between operating points. Every switchman, substation operator, and generating station operator is usually allowed to do all that he can without coordinating direction from the local system operator who in turn handles all he possibly can in his area without coordinating direction from the system operator. Methods of procedure and standard practises are established through written operating instructions so as to reduce to a minimum the amount of direction necessary both in emergency and in normal operation. Complete and thorough training of all the operating personnel is essential to be sure that everyone can be counted upon to respond promptly as expected and thus get harmonized action over large areas though individuals in the performance do not know what other individuals are simultaneously doing.

When such a system is well established with well trained personnel, lightning storms and similar emergencies are satisfactorily handled without any one person being acquainted with all that is taking place. In fact it often becomes necessary to spend some little time on assembled records in order to determine what actually has happened and whether or not the equipment and personnel have functioned properly.

The operating personnel must have a broad knowledge of surrounding system conditions to accomplish this harmonized performance. Such continuous information on system conditions as will assist in performing the function of a particular operating point must get to that point. Changes in generation to compensate for differences in actual and scheduled load conditions require a convenient method for the system operator to determine the most economical adjustment. Methods of correlating and automatically acting upon information are being developed and will undoubtedly be more widely applied.

Local system operators and system operators must be increasingly able, well trained, experienced men, considerate and diplomatic, but with the broad knowledge and judgment necessary to make quick accurate decisions and translate them into action through direction over the telephone. The performance of the system in fulfilling its objective finally depends upon the quality of system operation. The importance of these men and their perfomance has not always been sufficiently appreciated and there is a shortage of well trained, well educated, able men.

Executing the Operating Plan on Interconnected System. An interconnected system operator coordinates the performance of the individual companies where centralized direction is provided on the interconnection. System operators do not report to the interconnected system operator any more than a switchboard operator reports to a local system operator. Only such coordinating directions are given and received in each case as are required to produce dependable, economical, unified operation. In neither case is there any need for loss of individual initiative or responsibility. The function of the interconnected system operator is in some cases simply assigned to some system operator by mutual consent of the companies involved.

Most existing interconnections have no centralized direction. The system operators of adjoining companies coordinate the performance of their companies and by such action progressing through the interconnected group produce unified operation. Many companies have handled their own operation in exactly the same manner between the switchboard operators at two or three generating stations before system operators were justified. The effectiveness of the decentralized method is increased by occasional meetings of those directing the operation of the individual companies. Operating problems and practises are reviewed and mutual agreement reached on methods of procedure.

In a closed loop interconnection without phase shifting transformers or other special equipment it is impossible to direct the power flow. Adjustments can only be made for the individual company's conditions by so regulating that company's generation as to produce the net power flow desired. No satisfactory method of accounting for equities in interconnected loop operation through several companies has yet been developed.

Little attention is paid to the power flow on tie lines in a system under one ownership until there is danger of reaching some physical limitation on the circuit. Power flow on tie lines between different ownerships in interconnection however, becomes one of the bases on which money is exchanged. All the different classes of power referred to in Mr. Bauhan's paper have different values and even the same type or classification will have different values at different times. It becomes part of the execution of the operating plan in interconnection therefore, to sort out, classify, and account for the different classes of power flowing. Unless care is exercised in establishing the principles not only in operation but in the contract, this work is likely to become excessively complicated.

So-called incidental or uncontrollable power will flow across the interconnection as long as the properties are synchronized even though no power flow is scheduled. It is necessary, therefore, to have an incidental rate which will encourage complete utilization of the instantaneous diversity without penalizing anyone.

An encouraging emergency rate which will induce everyone to rely upon the interconnection reserve, but which will at the same time adequately compensate those properties producing the power in an emergency, is necessary. The rate used for a sustained emergency must compensate the property supplying the capacity and yet not too severely penalize the company using the capacity unless the necessity for this use has arisen from negligence in maintenance, poor planning in development, or willful leaning to prevent investment in capacity.

SUMMARY

The possibilities of interconnection can be realized only when the system is effectively developed and operated.

The interconnected system is an electric supply unit which functions like a similar system under one ownership. Such differences as exist result either from the larger size of the interconnected system or from the multiplicity of interests resulting from the number of ownerships involved.

Possibly there are some limits to the size of the interconnected system and the degree of coordination desirable between ownerships. Sufficient coordination to satisfactorily operate closed loops involving several companies is becoming essential. Ample facilities should be provided to simplify the operation as much as possible.

Is not interconnection much like democratic government in which the companies are the individuals? The total benefits to be shared are in proportion to the total participation and the regulation imposed on the individual participants should be the minimum necessary to make the mutually attainable benefits proportionately available to all.

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Discussion

INTERCONNECTION SERVICES

(Bauhan)

INTERCONNECTION—NEW ENGLAND DISTRICT

(Dillard and Bell)

PENNSYLVANIA-OHIO-WEST VIRGINIA INTERCONNECTION

(Fitch)

INTERCONNECTION DEVELOPMENT AND OPERATION

(Keenan)

H. K. Sels: Mr. Bauhan has presented very logical and lucid definitions of interconnection and the various services to be rendered by it. As a member of a group working on definitions under the direction of the Joint Interconnections Subcommittee I should like to see these definitions accepted as a standard. One engineer refers to load diversity where another calls it peak diversity and economy flow called dump power. If these terms could be standardized it would prevent possible confusion and misunderstandings. It would serve to fix the relative importance of the various services in engineering design as undoubtedly each class of service will justify different amounts of spare capacity and equipment. For example, economy flow might not justify any spare capacity or equipment where undoubtedly firm power could justify sufficient spare equipment to insure a high continuity of service. In contractual relations accepted definitions would provide useful terms in writing contracts which would have a better legal status.

To amplify Mr. Keenan's example of a multifamily house compared to interconnection and the cooperation necessary, it would be possible for a group of families to have things in common such as billiard rooms and ballrooms. So too with interconnections it is possible to have common plants built economically at the most desirable location to obtain maximum operating economies. In this way individual plants would become more or less independent of the load and the problem then becomes how to operate the total generation plant the most efficiently. So we have a concentration and saving in generation compared to a lesser addition of transmission and distribution. While systems will continue to grow due to consolidations interconnection has and will continue to increase materially the size of systems.

Attention may be called to the added importance of load and frequency control and the importance of investigations of lightning in transmission lines, development of standard test waves, and coordination of insulation with interconnection. Incorporating in our standards the results of some of the investigations will facilitate the development of interconnected systems in a standardized and economical manner.

H. G. Harvey: Mr. Bauhan's paper deals primarily with the interchange of power or kilowatts between operating companies. However, the phraseology of his paper throughout indicates that he had the interchange of reactive kva., or voltage control very clearly in mind although he did not specifically mention it. It might be pointed out that with a few very obvious modifications, the main service divisions which he outlined can be applied to reactive kva. as well as to true power flow or kilowatts.

There is a subdivision of his first division "Emergency Service" which Mr. Bauhan does not bring out in his paper, probably because it does not affect contracts. However, since it is a potential source of difficulty it might be well to point it out.

What is ordinarily thought of as emergency service, lasts for an appreciable length of time, anywhere from 15 minutes to a number of days or even weeks. However, there is another class of emergency service, of a more transitory nature, which lasts from something like one-half a second to one or two minutes. This occurs, for example, when a distant tie line or generator comes off the line due to a switching operation and a surge or bump is thereby set up in the system. Under such conditions, the presence of the interconnection may mean the difference between dropping load and riding through successfully. The value of this service naturally cannot be measured by the power taken over the interconnection during the very limited time necessary for the readjustment of the load to a normal condition. In instances where a company with a relatively low standard of service is interconnected with a company with relatively high standard of service, the result of the interconnection is that the first company gets a higher grade of service, with fewer momentary interruptions, while the second company may have a lower grade of service with more voltage disturbances and the like as a result of the interconnection. As far as I know, no means have as yet been devised to adjust equitably for this condition. I have, however, known of cases where this condition has been a source of friction and difficulties among the load dispatchers and that part of the operating personnel charged with the control of the actual physical interconnection.

M. M. Samuels: Engineers are prone to forget the fact that the answer to the majority of engineering investigations should not be of an engineering but of an economic character, because in the final analysis, the answers must be submitted to executives in simple form, and executives are satisfied to let the engineers go through with elaborate engineering investigations, but they are not satisfied with engineering answers; they must have economic answers. Mr. Bauhan correctly stresses the economic side. Yet he does not altogether eliminate intermediate engineering features from his answers.

Since fixed charges make up the principal part in the cost of a kilowatt-hour, it is important that an attempt be made to come to a definite understanding as to what items enter into fixed charges. Steam plant fixed charges are variously given between 10 and 18 per cent, substation fixed charges are found given as low as 8 per cent and as high as 17 per cent. This is not caused by the fact that one plant actually shows a lower fixed charge than another, but that one considers an item a fixed charge, whereas the other considers the same item an operating charge. Furthermore Mr. Bauhan speaks of the "fixed element of production expense" and goes so far as to say correctly that the effect of its avoidance is "similar to avoided fixed charges." This method is universal, but why? If it is a fixed charge, and everyone, including Mr. Bauhan, seems to agree that it is, why not call it a fixed charge and include it as an item in the total fixed charges?

The evaluation as described in the second chapter of the paper, with its subdivision, is very logical and systematic, but it is of an intermediate nature and not the final analysis to be presented to executives. Under the heading "Capital Cost Savings," Mr. Bauhan states: "and they are in any event of importance to the executives who are concerned with financing the project." In this remark lies the key to the incompleteness of Mr. Bauhan's second chapter. He considers the engineering features as of primary importance and the purely financial and economic features of interest to executives as of secondary importance, whereas the reverse is the case. It is no doubt for this reason that he discusses production in such detail. The following are suggestions in systematic form of what is of interest to executives, and what should finally be presented to them for *each year* of *each plan after* the evaluation feature studies suggested by Mr. Bauhan have been completed.

1. Total kilowatt-hours delivered to load centers, whether generated or purchased, for each year, each plan, each system.
2. Total cost per kilowatt-hour at load center for each year, each plan, each system.
3. Over-all plant factor of all generating stations for each year, each plan, each system.
4. Capital to be invested each year, each plan, each system.
5. Degree of reliability for each year, each plan, each system.

Total Kilowatt-Hour Delivered to Load Center. The executives are not interested so much in the kilowatt-hour generated or purchased, but more in the kilowatt-hour delivered to load center for distribution. As a matter of fact, they are really interested only in the cost per kilowatt-hour delivered to customers. It is quite fair and sufficient for the range of Mr. Bauhan's paper to estimate energy delivered to load center, because the distribution will be the same whether there is interconnection or not.

Over-All Plant Factor. It would seem offhand that the plant factor would be of very little interest after capital investment and cost per kilowatt-hour are known. But it is of interest as an indication of plant utilization, and if the plant factor is low, some explanation is often called for.

Capital Investment. The cost of energy is not always the only determining factor for the adoption of a plan. Sometimes it may be advisable to have a higher energy cost if it can be done at a lower investment. Market conditions, uncertainty as to future load, and other features may make high investments inadvisable even if they appear to promise economies.

Degree of Reliability. Absolute reliability can only be had with plants that are shut down. With plants and lines in operation, reliability is a matter of degree, and a decision must be made in each case as to the degree of reliability that can be obtained for a definite price. It would be well to discuss this matter further and eventually establish standards for degrees of reliability. The following ratings are suggested:

A. Each load center has sufficient local generating capacity for emergency and also at least one incoming outside source.

B. Same as A, except that some load centers have no outside source of supply.

C. Some load centers have insufficient generating capacity for emergency, but at least two incoming sources from outside, each at least a double circuit.

D. Same as C, except single circuit.

E. One source, double circuit.

F. One source, single circuit.

The estimated degree of reliability should be given for each important load center, for each plan, each year, each system.

In conclusion, I want to mention that at present it is very difficult to make any rational prediction as to future load. President Hoover estimates a growth of 25,000,000 hp. in generating capacity for the next 20 years. Translated into kilowatt-hours, this figure would seem extremely conservative; and yet the President is generally sure of his figures. Perhaps he had in mind that more kilowatt-hours can be gotten out of existing equipment. The growth of per caput consumption and the resulting per caput generation are likewise quite doubtful. Just now it is difficult to use past statistics to estimate future requirements. This uncertainty should lead to more interconnections, but there are cases in which the same uncertainty will prevent interconnection.

L. L. Perry: The operation of widely interconnected systems, whether under one ownership or under several ownerships, has already demonstrated, as so many executives and operators well know, the improvements in power supply that are obtained in several particulars, such as

1. Lower fixed charges.
2. Better operating economy.
3. More uniform frequency.
4. Lessened voltage fluctuations.
5. More reliable service during major accidents incident to power station and transmission operation.

As Messrs. Dillard and Bell point out, executive staffs and operation staffs are undergoing an evolution. Operational supervision of interconnected systems is being delegated to one central group. This will enable each interconnected section to reap the benefits of interconnection such as those enumerated above without sacrificing appreciably any important assets of separate operation.

There are several lines along which rapid developments are to be expected. Little is said in these papers about actual experience with simultaneous automatic frequency control at several power stations in an interconnected system, although as mentioned in Mr. Fitch's paper experimental equipment is now in place for this and experiments are in hand. Widely different ideas exist as to what such automatic frequency control equipment does and should do, but I am confident great progress will be made in reducing instantaneous fluctuations on regulating stations and main tie lines, at the same time getting improved frequency.

Few transformer phase control equipments are yet in service. Yet, as overhead and underground circuits get loaded to capacity, economics will dictate their installation in some instances, particularly where it is desirable to close loops and still have control of power flow. Where buses at strategic points are tied together through circuits of different voltages, satisfactory operation has been attained, both in the east and in the west, in several instances without transformer phase control, but in other instances studies show that it will be very difficult to make the higher voltage line properly share the load with the lower voltage line unless transformer phase control equipment is installed. In instances where parallel circuits of the same voltage follow routes differing greatly in length, sometimes load ratio control will produce sufficiently equal division of current, even though most of the kilowatts take one route and most of the reactive kilovolt-amperes take the other with the result that the cost of phase control equipment is not justified.

H. R. Kurth: The pioneer efforts of New England companies in solidifying the several systems through the medium of interconnection has been amply justified by the savings in operating expense, and the mutual assistance rendered during periods of stress. Illustrative of this foresight is the 110,000-volt connection between Edgar Station and Millbury which was originally erected without contract but over which large quantities of secondary power have been transferred.

During dry seasons sales of surplus steam power by the Edison Electric Illuminating Company of Boston have totaled sixteen million kilowatt-hours in a single month and this spring purchases of dump hydro power exceeded thirty-six million kilowatt-hours during April alone. At some periods of the year the normal lighting peak characteristic load curve of Edgar Station has been converted to nearly a flat load, with greatly improved load factor, by the sale of surplus steam power during the lighter load period and purchase of firm power over the peak. During other times the purchase of dump hydro power causes a lowered load factor, but the over-all system economy is simultaneously greatly improved due to the low net cost of the surplus hydro power. Interconnections of ample capacity have permitted operation for maximum over-all economy of the several systems without loss of their corporate identities.

There remains however between some sections of the interconnected systems certain tie lines whose inadequate capacity causes frequent trip-outs with resultant upsets in load distribution, frequency, and voltage, the effect of which upon our customers may not receive sufficient recognition. Those industries employing continuous processes, dependent on a steady flow of energy at constant frequency and voltage are at times seriously affected by the heavy fluctuations which accompany the tie line interruptions.

The stability of tie line operation is directly determined by the degree of accuracy with which each system regulates frequency at its own stations. It should not be a normal function of interconnected companies to maintain frequency by changing tie line load because of laxity on the part of another system in changing generation in step with its own load.

The existence of long transmission line loops through several systems permits maximum protection to the several systems with the loop closed, but undesirable power flow around the loop frequently causes them to be operated open, with less stable operation of tie lines. The introduction of phase angle shifting devices into the loops seems inevitable for most satisfactory operation.

The high grade of service normally rendered by the metropolitan type of system utilizing underground transmission methods perhaps makes its customers particularly susceptible to disturbances transmitted from another system through interconnections. The more severe of those disturbances, occurring during lightning storms, sometimes force separation of the interconnected systems in the interest of reducing the area affected.

The occasional very severe disturbances due to loss of a large amount of interconnected system capacity has several times caused a load pick-up on the Edison system of 70,000 kilowatts without undue distress, thereby indicating the adequacy of the policy of protecting the largest single unit, be it generator or tie line. In the process of restoration to normal frequency and voltage the stations previously designated to pick up such load shifts may be dilatory in functioning, forcing other systems to assume the burden of load pick-up.

These difficulties encountered in interconnection operation are frequently accentuated by inadequate communication and metering facilities. The Edison load dispatcher has direct telephone lines to the system operators of the New England Power and Eastern Massachusetts Electric systems.

Past experience indicates that the success of interconnection operation depends primarily on the cooperation existing between the several system operators, and we are pleased to report that the spirit of cooperation is paramount in New England.

S. S. Seyfert: The analysis of the services and economics through interconnection made by Mr. Bauhan is most logical and complete. Messrs. Dillard and Bell point out the fact that these services and economics are considerably augmented under unified ownership or control. Mr. Fitch, in his paper, makes the point that mutual understanding and good will among companies may produce the same advantages in kind as common ownership. In either of these two cases there is presented to the public a condition that suggests a "power trust."

The public has now long accepted the idea of the power company as an economically desirable monopoly within its territorial limits. It has also accepted the almost complete integration of the wire communication system as working toward the greatest good of all. The numerous interconnections already effected or in the making have created a new situation in the power field which immediately suggests or even calls for a fuller degree of integration than now obtains. It would seem that if the public could be educated as to the advantages and possibilities of interconnection and integration, and if the facts engineers are fully aware of could be expressed in their own terms and divorced from our technical language, it could be brought to stand behind and support our integrated power systems financially and otherwise as it has done for other worthy projects in the past.

A. H. Sweetnam: The Edison Electric Illuminating Company of Boston is the largest single customer of the New England Power Association and as such has been keenly interested in the development of the system of the New England Power Association, and in its interconnection activities with other New England systems.

The first attempt at interconnection with the Boston system was initiated in an effort to utilize the facilities of both systems in providing capacity needed in the minimum time and with the least investment. This connection, looked upon in the light of later developments, was a very limited attempt to apply the principles of interconnection.

The capacity of the connection was approximately 15,000 kva., and is made at 66 kv., with lower voltage transmission through the thickly settled portions of the city of Boston. The line is on wooden poles and transformers are without ready means of tap changing, which has somewhat handicapped both parties in the use of the connection to maximum advantage, as the power factor at which the line operates is not under control. The relay system initially was not adequate, and the capacity of the tie is so small in comparison with the capacity of the systems interconnected, that it is often unstable at times of system disturbance.

In recent years the operation of this line has been improved by modernizing the relay system, and by the installation of synchronous condenser capacity at the approximate midpoint of the line. The capacity of the connection has also been increased to 22,500 kva. by adding water cooling connections to the transformers.

The next interconnection, made a few years later, was of very much larger capacity, and utilized modern methods in the control of reactive energy. This connection was made between the Edison Company's new Edgar steam station and the largest dispatching center of the New England system at Millbury. It consists of a double circuit 110-kv. steel tower line with a nominal capacity of 100,000 kva. Transformers at the Edgar Station are now of 75,000-kva. capacity and are equipped for tap changing under load. There are two distributing substations of the Edison Company on this line, one of 30,000-kva. capacity, and one of 5,000 kva. This line was built, as has been mentioned in the paper, without formal contract between the parties, but with the knowledge that once in service it would serve for mutual support and provide opportunities for power interchange on a profitable basis. Experience has indicated the wisdom of this construction, as instances are numerous of the benefits of mutual support and the accounts of both companies show substantial amounts saved due to interchange operations.

The next interconnection was accomplished, not on the basis of interchange, but on the purchase of prime power from the New England system in lieu of the construction at that time of a new steam station by the Edison Company on the waterfront to the north of the city. This prime power is taken at the Woburn Station in the northern section of the Company's territory. By agreement energy can be sent from the Edgar Station on the south to the New England Power Association's system at Millbury, and a like amount drawn from the Association lines at Tewksbury and delivered to the Woburn Substation on the north. This receiving point on the north will be connected later with the proposed steam station just mentioned, when the additional distribution facilities and steam capacity are required.

One very marked saving accomplished by the agreement permitting power transfer from Edgar Station via New England Power Association's lines to the Woburn Station, was the postponing for the time being of a program which was then being actively considered by the company calling for the construction of a 110-kv. double circuit tower line from a point on the line between Edgar and Millbury to the present receiving point on the north at Woburn. This line would have accomplished the same transfer of power as is now possible via the lines of the New England Company. Thus duplication in the construction of some 30 to 40 miles of line was avoided.

At the Woburn Substation transformers are equipped with load ratio control and synchronous condensers are provided. When the connection is made to the new generating station, which will in turn be connected to existing stations, there will be need for phase angle control equipment.

It will be noted that the Edison Company has equipped itself at all important transformer banks involved in these interconnections with facilities for tap changing under load, and with synchronous condensers, and is contemplating phase angle control equipment. It is felt that in the not distant future the necessity for more accurate control of kilowatts and kilovolt-amperes and voltages will necessitate the more general use of this class of equipment, and that the New England Company has been exceptionally fortunate in being able to operate to the satisfaction of so many interconnected parties, without having as yet to resort to this refinement and consequent expense.

The interconnection activities with the New England Company have indicated very plainly the advantage and necessity for the closest cooperation in the development of the relaying system as applied to the interconnecting lines.

Frequency troubles were numerous in the early days, but these have now disappeared entirely as a result of the application of automatic frequency control equipment. Interconnection brings increasing voltage disturbances, but these undoubtedly will be gradually overcome by improved switching and relaying equipment and by more adequate shielding of lines.

We wish to lay particular emphasis on one point mentioned by Messrs. Dillard and Bell, that of the importance to the successful operation of any interconnection of a mutual spirit of cooperation and good will regardless of formal contracts.

Alex. E. Bauhan: Mr. Sels has intimated that the general adoption of a nomenclature for interconnection services would improve the legal status of interconnection contracts. This is very true. In the absence of a nomenclature generally accepted by the industry it is necessary for the various services to be specified and defined in considerable detail in the interconnection contracts. Several paragraphs may be required to give the same meaning as a few words from an accepted nomenclature. A nomenclature generally accepted by the industry will be given due recognition by the courts. This is, therefore, one good reason why it might be advisable to develop an official nomenclature for interconnection services.

Mr. Harvey points out that one of the services rendered by interconnection is the amelioration of voltage fluctuations due to minor disturbances and that the benefits resulting therefrom are difficult to evaluate. It is of course quite true that this service exists and under the present classification it is undoubtedly a manifestation of emergency service. Because of its difficulty of measurement and evaluation it must be considered as one of the several intangible benefits which arise from interconnection.

In calling attention to the reactive component service which might be rendered by an interconnection, Mr. Harvey touches on a subject which was considered in the preparation of the paper but left out in the interest of simplicity and brevity. The reactive component service rendered by an interconnection can be classified very much the same as the energy service. All of the main classifications which have been offered, with the exception of that designated as *storage power*, are applicable to reactive component transactions. It may be mentioned that my own company has been engaged in reactive component economy-flow transactions with one of its neighboring companies—reactive component from synchronous condensers being supplied by one of the companies in replacement of the more expensive supply of reactive component from a turbine generator in the system of the other company.

A classification such as presented in the paper, as Mr. Samuels remarks, is not the result of a brief examination of the subject, but rather the result of several years of development and experience as well as of an analysis of what services are being undertaken and contracted for in the industry generally.

Mr. Samuels is of the opinion that fixed element of production expense can be combined with fixed charges and considered as a single item in any evaluation procedure. It is true that the fixed element of production expense behaves very similarly to fixed charges and I see no objection to their being combined for report purposes. However, they arise from entirely distinct accounts and must in any event be separately determined in anything but the most superficial study.

Mr. Samuels also gives a word of caution regarding the uncertainty of future loads and installation plans. We engineers are prone to set up certain basic assumptions in our studies involving loads and development programs and then after performing various cleancut mathematical operations, arrive at a conclusion which we regard as definite and infallible. As Mr. Samuels states, the estimation of future loads is fraught with uncertainty and notwithstanding the fact that development programs are frequently laid out for ten or more years in advance it is doubtful that such programs can be dependably predicted more than three years in advance. The results of evaluation calculations must therefore be used with good judgment.

Professor Seyfert believes that the contents of the papers of this session should be made available generally to the public in non-technical language to show what the much-maligned power utilities are doing by interconnections and mergers to reduce the cost of electric service. In this connection I am prompted to venture an opinion as to the effectiveness with which these interconnection savings are realized under independent operation and under merged operation. My guess would be that ordinarily something in the order of 50 per cent of the possible savings are realized in interconnection between companies. With the application of an unusual degree of skill in the discovery of these savings and their realization by well conceived contractual relationships possibly an upper limit of 80 per cent of the savings can be realized. With merger and consolidation of the system operations substantially all of the savings are realized.

Mr. Sibley states that in his own systems the savings from economy flow are relatively small, being of the order of 5 per cent of the total production expense. This is the usual experience, although in some few cases the economy-flow saving is the main justification for the interconnection and is sizeable. In the 220,000-volt interconnection which my own company has entered into with companies in eastern Pennsylvania the main justification for the interconnection arose from load diversity. Since it has been in partial operation we have discovered, however, that the capacity savings arising from emergency service are still more important than those arising from load diversity. The savings arising from economy flow, in this case, though appreciable, are relatively unimportant, appearing to be about 5 or 10 per cent of the total. Those savings which result in the avoidance of capacity installation are generally far more important than the relatively small production-expense savings arising from economy flow. Nevertheless, small or large, a saving is a saving and should not be overlooked, especially since economy-flow savings are so easily realizeable.

I. M. Moultrop: The paper by Messrs. Dillard and Bell gives much valuable information on the subject of natural interconnection in the New England District, and emphasizes many of its advantages.

One point not touched on is that of frequency control. In the past many people have felt that there was serious difficulty in connecting hydro with steam plant, because the frequency control of the hydro plant was not up to the same quality as that of the steam plant. This was undoubtedly true a while back, but need not be true today. The engineers of the Boston Edison Company can speak from actual experience on this subject; and they wish to go on record that when the hydro plant is operated with frequency control equal to that of our steam plant, the frequency is kept uniformly to a high standard. By means of improved apparatus and more care in operating, the hydro company is matching us in the quality of its frequency control and possibly under certain conditions of load the hydro plant is a little better than the steam plant. No one need to hesitate in the future about tying steam plant and hydroelectric plant together so far as the matter of frequency control is concerned.

Another point that is very essential to good service over an interconnection is load dispatching. The load dispatchers of the two systems must be in close contact with one another. It is not necessary for the load dispatching of both systems to be under one control, and it is probably better for each system to have its own load dispatcher, but they must cooperate and work in harmony with one another. One thing that will materially help this is the load dispatchers conferences that are held at intervals where the interested people of both systems get together, discuss their mutual and particular problems and exchange ideas. All these things are very helpful, but what is equally helpful is establishing the personal relationship between the two groups of load dispatchers. When two persons are sufficiently acquainted to call each other by their first names and meet at frequent intervals to discuss their work, they come to understand each other and each acquires a respect for the other's ability and his problems, thereby eliminating much friction and misunderstanding. This is working out very well indeed with the New England Power System and the Boston Edison Company.

Communication Services of Electric Utilities Underlying Considerations

BY R. N. CONWELL,[1] Fellow, A. I. E. E.
G. M. KEENAN,[2] Fellow, A. I. E. E.
C. F. CRAIG,[3] Member, A. I. E. E.
and
E. C. BRIGGS[4] Non-member

Synopsis.—The paper outlines the communication requirements of electric utilities and suggests effective methods for meeting those requirements. Operating, customer service, and administrative activities are considered separately. However, the advantages of a unified communication system for all activities are outlined.

The relative merits of cable, open wire, power line carrier and radio are reviewed. The use of communication channels for telemetering and supervisory control purposes is discussed.

The desirability of basic plans for establishing and operating communication systems for electric utilities is discussed in detail.

THE elements of an electric utility must be effectively coordinated in operation to provide satisfactory electric service to the customer. A properly designed and constructed electric system, adequate tools and able personnel are essential, but until all of these elements are coordinated and operated as an electric supply unit, no service is rendered and no revenue earned.

Effective coordination of the activities of an electric utility necessitates the establishment of communication channels for the continuous flow of information into organization centers and the prompt transmission of orders and suggestions from these centers to the points where action is taken. This paper outlines the communication requirements of an electric utility and suggests effective methods for meeting those requirements. Particular attention is given to voice communication, as it seems to be especially adapted to the requirements of the electric utility. This is evidenced by the fact that about 85 per cent of the electric utility's communication expense is for the transmission of the spoken word. The use of the word "communication" throughout the paper assumes that the path used may be cable or open wire, power line carrier current or radio, either privately owned or leased.

The work of an electric utility may be considered as divided into three classes of activities:

1. Operating activities, including dispatching, generating and substation operation, emergency line patrolling and repairs.
2. Customer service activities, including new installations, disconnects, moves, service complaints, and comments, and
3. Administrative activities, including administrative sales and business functions as differentiated from the service functions.

OPERATING ACTIVITIES

Fig. 1 shows a typical organization for the handling of activities classed as "operation," and indicates the communication channels usually available for the necessary flow of information between controlling centers and the points where action originates. A complete picture of happenings on the system at any one moment is rarely available immediately because operation is simplified and speeded up by allowing each operating center to proceed on its own responsibility until the need for coordination with other operating points becomes essential. When this need arises, direction must be introduced from a dispatching point which may be the directing center of the generating or substation, a local dispatching office, a local system

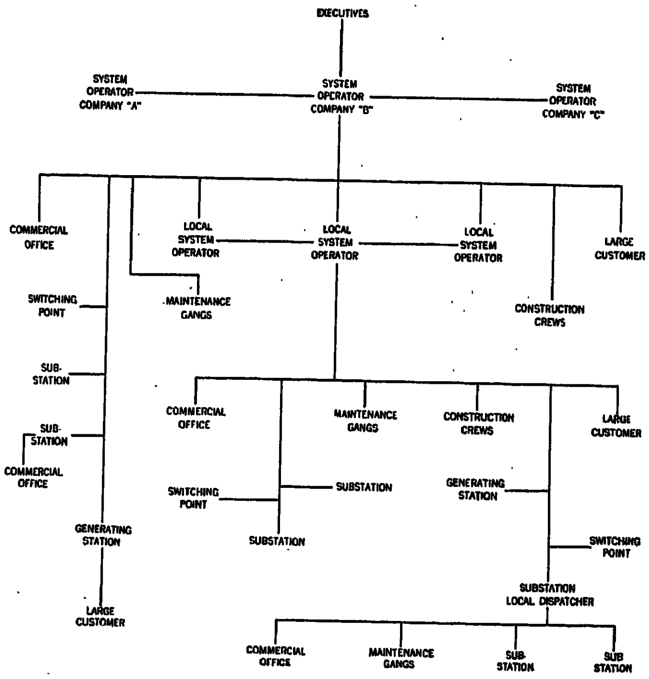

FIG. 1—TYPICAL ARRANGEMENT OF COMMUNICATION CHANNELS FOR OPERATING ACTIVITIES OF ELECTRIC UTILITIES

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[1] Trans. and Substation Engr., Public Service Elec. and Gas Co., Newark, N. J.

[2] Supt. of Penn-New Jersey Interconnection, Hazelton, Pa.

[3] Special Representative, American Tel. and Tel. Co., New York.

[4] Communication Engineer, The Ohio Bell Telephone Company, Cleveland, Ohio.

*The authors constitute a subcommittee of the Power Transmission and Substation and Communication Committees.

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operating office or the operating office for the entire system.

The communication facilities for operating activities need to be:

1. Easy to operate and so arranged that communication service can be established quickly.
2. Available at times when generating and distributing facilities are in trouble and, therefore, as far as possible, not subject to the same hazards as power facilities.
3. Of such quality as to avoid misunderstandings and permit conversations to be carried on with ease.
4. Safe for use but not so protected as to be unavailable for service during electric service difficulties, and
5. Of sufficient capacity so that under the worst emergency conditions no serious delays will be experienced in restoring electric service.

Heavy or important traffic requires the establishment of direct channels. Relatively light or unimportant traffic may be handled over routes established by connecting two or more direct channels together. Switched connections of this latter type tend to create transmission and signaling difficulties, and for this reason, are kept at a minimum. Two or more independent paths are essential where continuous service is to be provided. One of these paths may be designated as the regular or direct route over which a satisfactory grade of transmission is required at all times. The other or back-up route may provide a somewhat lower grade of transmission, but it must be satisfactory for the handling of essential communication during times when the regular route is not available. Diagrams showing the regular and emergency routes for calls between specified points are helpful in properly distributing the traffic in the larger systems.

Many operating points, such as generating stations and substations, require communication between their central control station and other locations on the same premises. For example, in a large substation, the power switchboard is usually the central control point, with communication facilities required between that point and repairmen's quarters, high-tension room, pump house, and switch yards, and possibly other locations. In generating stations communication facilities are required from the central point to locations where coal and ashes are handled, to the boilers, turbines, pumps, switch yards, etc.

The equipment provided at generating or substations to terminate communication channels may be either manual or dial. Dial equipment will generally be desirable in those cases where most of the traffic is confined to intercommunication between telephone stations on the same premises and complicated tie lines or long extensions do not have an important bearing.

At points where small private branch exchange switchboards are installed, it may be difficult to establish convenient arrangements for answering calls at these switchboards at night. In some of these cases night connections have been established through the P. B. X. and in other cases it has been arranged for the communication utility to answer these calls at its central office and properly route them just as would a private branch exchange switchboard operator.

Dispatchers require communication channels to practically all operating points on the system, and, in certain cases, to locations along the transmission lines, to the various departments and officials of the company, to large power customers, and to system operators of interconnected utilities.

Various equipment arrangements have been provided at dispatching points for the termination of communication channels. The cordless type of equipment, where answering, ringing, and holding features are obtained by merely operating a key, is usually considered the simplest and most convenient arrangement. This type of equipment, illustrated in Fig. 2, appears suitable for use where not more than 50 channels are to be terminated or where the need for simultaneous through connections does not exceed five. Where more than 50 channels or more than five through connections are involved, it is necessary to use the familiar cord and plug type arrangements. With either type of equipment, it is usually necessary to limit the height of the turret in order that the dispatcher may have an unobscured view of the power system diagram board. This requirement is met by special assemblies whereby the height of the cord and plug turret may be reduced to about six inches, or by the use of slant-faced cordless turrets, or by sinking the equipment in the top of the dispatcher's desk.

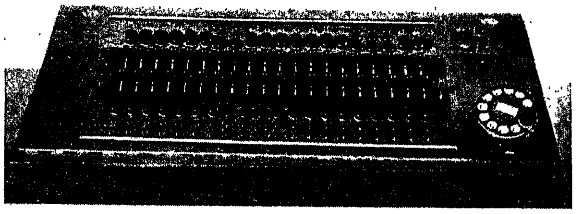

Fig. 2—Typical Cordless Turret for Terminatión of Communication Channels

Convenient arrangements are desirable for transmitting routine information such as meter readings, switching orders, etc., required in connection with load dispatching work. Teletypewriters, which provide a typed record, are used to some extent for such work. This apparatus provides a means whereby the dispatcher may deal simultaneously with generating plants and substations. Objections have been raised to teletypewriter service on the basis that the employees using it must acquire some degree of facility in operating a keyboard. This objection should not prove serious, however, and there is some probability that the teletypewriter will provide a valuable service to supplement the telephone in power dispatching work.

Some electric utilities have considered it advisable to install devices on the private dispatching lines for recording the telephone conversations of load dispatchers. The wax records used are kept for reference purposes until there is no likelihood that need will arise for transcribing the conversations. Reports as to the results obtained are favorable. Improvement is noted in the work of the load dispatchers, and from the standpoint of management, such arrangements are valuable in that responsibility can usually be definitely fixed in case the need arises for reviewing past operations.

Little progress has been made toward standardizing equipment arrangements for load dispatchers. Considerable study of existing installations and analysis of results obtained will be necessary before definite conclusions can be drawn as to the arrangements which are most desirable.

Disturbances occurring on a power system may make it necessary to reach patrolmen and line foremen to perform switching operations and emergency repair work. When a power line has failed it is the usual practise to patrol simultaneously small sections of the line to determine the location of the trouble. After the trouble has been localized and repair work started, need may develop for communication between the repair crews and the dispatching point. Communication facilities necessary in this connection have been provided in several different ways. Patrolmen have been furnished with portable telephone equipment suitable for connection to open-wire communication circuits at any point along the power line right-of-way. Other companies have considered the portable equipment too cumbersome and have established permanent communication stations along the transmission lines. These permanent stations have been connected in most cases to lines along the right-of-way, in a few cases to spur lines connected to trunk lines off the right-of-way, and occasionally to antennas used in connection with power line carrier-current channels.

Detailed reviews of representative reports of patrolmen indicate that the need for separate communication circuits for this purpose may be over-emphasized. However, much depends upon whether the territory traversed by the transmission line is thinly or thickly settled and upon the relative importance of maintaining uninterrupted power service over a particular route. Apparently, each situation requires individual study and engineering to determine its particular requirements.

The value of telemetering, remote indicating, and supervisory control services in effecting centralized control of a power system is rapidly gaining wide recognition. Where long distances are involved, apparatus operated by direct current over separate channels or by means of impulses sent over narrow frequency channels appears to be the most economical. For shorter hauls, the cost of conductors is usually not controlling, and simple terminal apparatus using separate wires for each metering or control service seems to be the most economical and desirable. Since large investments in power equipment are normally involved, and manual assistance cannot be obtained quickly at unattended stations, the conductors used must give reliable service.

The present methods of regulating frequency are not considered satisfactory in some of the larger electric systems. Arrangements are desired which will permit the sharing of frequency control by several generating plants or possibly, in the ultimate, provide for load distribution to stations on an automatic basis in direct proportion to the relative costs of generation. Apparatus has been installed and tests are under way to determine the possibility of obtaining independent regulation of frequency at each generating plant to such close limits that more than one station can share in the frequency control. Another plan which has been suggested contemplates the use of a constant frequency supply which might be furnished over communication channels and used to synchronize frequency controlling devices in generating plants. A quartz crystal oscillator circuit used in conjunction with vacuum tube circuits for control would probably provide the most stable and conveniently controlled source of constant frequency. Fig. 3 shows such a standard, now available in laboratory form, which has a frequency stability of approximately one part in ten million or about three seconds in one year. This apparatus together with suitable telephone conductors or channels should provide a satisfactory means of synchronization for power frequency control purposes, should the need develop.

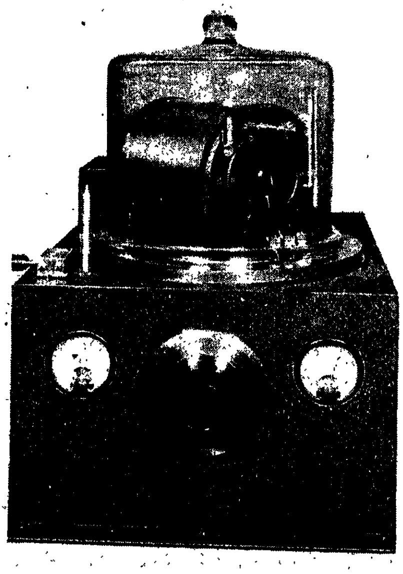

Fig. 3—One Complete 100,000-Cycle Standard Frequency Unit

CUSTOMER SERVICE ACTIVITIES

The second principal class of electric utility activity is customer service.. Electric utility operation is devoted to the furnishing of a grade of service to the customer which he will consider entirely satisfactory. A vital factor in supplying such service is the provision of suitable means whereby the customer may easily and quickly convey to the utility his impressions and reactions in regard to his electric service. A large majority of the contacts with customers is made by telephone, and electric utilities have generally recognized the need for providing arrangements to insure that the customer calling by telephone will be handled as intelligently and courteously as if the call were made in person. In fact, greater importance is normally attached to telephone contacts because of the emergencies generally associated with such calls from the customer's point of view.

Customers are best satisfied when they deal with employees of the electric utility who can understand their problems and satisfactorily present the utility's attitude and service objectives. Experience indicates that the establishment of an organization especially trained and assigned exclusively to deal with the customer over the telephone is a most effective means of personalizing the service. Where this plan is in effect, all customer calls are routed to this personnel. Male attendants are considered necessary by some companies due to the character of the calls received and the feeling that men have a better understanding of technicalities. However, groups of trained female attendants have been assigned to this work with considerable success in a number of organizations recently established. Their generally pleasing method of handling telephone contacts tends to eliminate any feeling of irritation which the customers may have and usually leads to a mutually satisfactory disposition of the calls. Under this plan of centralized handling of customer calls, direct observations can be made to determine which practises are most effective in building up good will among the customers. Any desirable changes in practise can be put into effect quickly on a uniform basis.

Where centralized service bureaus are established, telephone lines are necessary between the bureau and the various departments in the company so that the attendants may readily obtain any information which may be necessary in transacting business with customers. The work of the bureau is simplified as much as possible by centralizing the file of customers' records, by short-cut methods of handling customers' orders, and by the installation of convenient arrangements of telephone facilities.

It is, of course, important that any service arrangements or commitments made over the telephone be carried out to the letter. The establishment of ideal communication arrangements and courteous treatment of customers calling by telephone will prove to be of little value if the actual service furnished and action taken with respect to complaints fall short of the customers' requirements.

ADMINISTRATIVE ACTIVITIES

Communication services are required by the electric utility for the handling of what may be broadly considered as administrative activities which include executive, legal, engineering, sales, and accounting matters together with certain features of the operating work where speed of action is not the governing factor. The electric utility's territory is divided into divisions and districts, with offices in central locations responsible for the conduct of administrative affairs over considerable areas. Communication service is required to keep these offices in touch with field forces and headquarters, and to maintain the necessary contact with other business concerns and individuals.

The type and volume of administrative activity handled by telephone generally necessitates extensive circuit and equipment arrangements. These communication facilities usually are provided by the telephone companies and it is important that the electric utilities make their objectives and requirements clear to the telephone companies so that the arrangements provided will accomplish the desired results.

The requirements for communication channels for administrative traffic are no different than those for similar traffic in other lines of business. Where the volume is sufficiently heavy, channels are leased for full time use. Arrangements may also be made with the telephone company for short period talking channels to be set up at certain specified hours of the day. Where the traffic is light, the public message channels of the telephone company usually provide satisfactory service.

Where quick transmission of letters, orders, accounting matters or other administrative affairs is necessary and a written record is desired, teletypewriter service has been found particularly helpful.

In those cases where it is necessary to reach employees who do not have a fixed post of duty, code-calling systems are often desirable. These may be installed in connection with private branch exchange systems or separately, as conditions may justify.

It is usually possible to install in the private branch exchange switchboard circuit and equipment arrangements for holding conferences by telephone.

Convenient switching plans are available which enable the secretary at a master station to answer and hold one or a number of controlled stations. The controlled station may have access to the master station line if desired. Switching plans are also available which allow an employee at one desk to answer calls on other lines without leaving his desk.

Sufficient attention has not generally been given to the location of private branch exchange switchboards. Such features as proper light, heat, ventilation, and quietness, which are essential to efficient operation, are frequently neglected. The private branch exchange operator is often loaded with a multiplicity of duties having no connection with her regular telephone operating work and the communication service naturally suffers. Highly satisfactory results are obtained in those cases where the operator's duties are restricted to work directly in connection with the operation of the switchboard.

METHODS OF PROVIDING COMMUNICATION CHANNELS

CABLE AND OPEN WIRE

Most of the communication channels used by electric utilities are obtained by means of cable and open-wire conductors. Cable is relatively free from trouble during storms and is considered a desirable type of facility. Open-wire channels are normally considered less desirable from the standpoint of continuity of service. However, in specific cases sufficient open-wire facilities are often available over the regular or alternate routes to ensure the desired reliability of communication. When necessary, extra guying, short spacing of poles and similar measures are employed to strengthen open-wire lines.

Open wires have been strung on the structures carrying power circuits or on separate poles along the power line rights-of-way. It has been the experience that open-wire circuits thus situated are normally subject to a large amount of interference, and disturbances occurring on the power wires may put the telephone circuits out of service completely at the time when they are most urgently required. In other cases the failure of telephone conductors has put the power lines out of service. As a result of these experiences and the improvement in other types of communication service available for the purpose, there is a growing disinclination to rely on open-wire telephone facilities routed along the same right-of-way with the power facilities over which service is to be protected.

POWER LINE CARRIER CURRENT

Communication channels are also provided for the use of electric utilities by means of power line carrier-current telephone apparatus. In a number of instances during storm breaks, power line carrier has provided the only means of communication available, and it is generally considered a reliable form of service. There appears to be a definite, but somewhat limited, application for this type of communication channel over long hauls where it is necessary to reach generating plants and substations in remote and sparsely settled locations. The cost of providing suitable cable or open-wire telephone facilities in such situations may be prohibitive.

Probably the chief difficulty experienced with carrier is the variation in quality and volume of transmission. The power line is not usually a simple circuit, but rather, is a part of an extensive high-voltage network and any switching or circuit changes in the network alter its communication characteristics. Choke coils have been used in branch circuits to assist in keeping the carrier current along the main channel and improved transmission has been obtained in some instances by this means. Difficulties have also been experienced in operating power line carrier successfully over long two-wire extensions or interconnecting it with two-wire circuits. These difficulties have in many instances had the effect of isolating the carrier channels from all other communication facilities. This arrangement does not appear to be flexible nor economical.

Opinions as to the value of carrier current differ and further experience is necessary in order to arrive at generally satisfactory conclusions as to the extent to which carrier current logically may be employed in an electric utility's communication system.

RADIO

A few companies have installed radio telegraph apparatus with the view of providing back-up service for the regular communication facilities. However, the necessity for employing licensed operators and the regulations limiting normal operating time to a ten-minute test period each day have not only made new installations unattractive, but have resulted in the abandonment of some of the original installations. No use is being made of point-to-point radio telephone channels due to lack of wavelength assignments and the high cost of securing the necessary reliability of communication. Considering the limitations placed on the use of radio channels and the other means of communication now available for use by electric utilities, it would seem that there is little field for radio in their communication systems.

CONSIDERATION OF SYSTEM COMMUNICATION REQUIREMENTS

Basic communication planning is necessary in order to coordinate individual services and facilitate the growth of the electric utility. It is, of course, desirable that maximum use be made of all communication facilities, that a satisfactory grade of communication service be available for instantaneous use at the principal operating points and that future needs be cared for slightly in advance of actual demand and without replacement of any large part of the existing communication facilities. These objectives cannot be met economically without establishing a basic communication plan for the electric supply system as a whole. It may be helpful, therefore, to consider somewhat in detail the information required and analytical methods which may be used in developing such basic plans.

DEVELOPMENT OF BASIC COMMUNICATION PLAN

In formulating a basic plan, it is highly desirable that close contacts be established for the interchange of ideas and information and for coordination of action by those concerned with the development, operation and maintenance of the electric utility's communication service. All departments of the electric utility are involved, together with the companies supplying communication services and facilities.

It is desirable that the basic communication plans adopted by electric utilities be developed along consistent lines. The extensive interchange of power between electric utilities and the frequent consolidation of operating properties is emphasizing the need for some degree of uniformity in the communication arrangements adopted by the various operating units in the industry. Each electric utility should determine its requirements for communication in the light of the overall objectives of the electric industry and should estimate for its particular territory what will be the probable effect of proposed changes in the territory served, in organization and in power operating practises upon its specific communication needs.

In conducting a detailed analysis of communication requirements a field inspection is made of representative sections of line and items of equipment in the existing communication system. Observations are made of the traffic passing over the private network. The volume and character of calls made over the telephone company's public message circuits is carefully studied. The average daily flow and hourly distribution of all telephone traffic is separated into incoming, outgoing, and intercommunicating classifications. Important calls are separated from those of a relatively unimportant nature. The average holding time is determined for the trunk lines to the telephone company's central offices and the tie lines between private branch exchanges. Busy conditions on individual station lines are noted. Particular attention is devoted to the volume and character of traffic during times of emergency. Methods of operating are carefully scrutinized. Studies are made of private branch exchange operating loads, including not only the operator's regularly assigned telephone duties, but also other special assignments such as secretarial or office work. Information with respect to the volume, character, and cost of communications handled by means other than the telephone is obtained.

UNIFICATION OF COMMUNICATION SERVICES

Basic plans for the communication services required by an electric utility may be developed either to provide for a unified system for all activities or separate communication facilities for particular activities.

Traffic loads and operating contingencies can usually be cared for with a greater margin of safety and with less expense where all telephone services and facilities are unified and operated as one system. In some companies, however, the needs of the operating department have appeared to be of sufficient importance and the traffic so heavy in volume that a communication network has been provided for the exclusive use of that department. In other territories where this has not seemed practicable, convenient switching arrangements have been installed which allow the operating department to seize quickly and hold any desired circuits for an indefinite period of time. These arrangements permit the exclusive use of circuits by the operating personnel whenever, in their opinion, such use is necessary and would seem to provide in effect the equivalent of an exclusive communication network.

In a number of instances communication studies have indicated that the best results could be secured through connection of the electric utility's privately owned communication plant to the facilities furnished by the telephone company. Mutually satisfactory interconnection arrangements have been agreed upon in such cases. Provision is made thereby for the complete interconnection of privately owned and leased communication facilities, thus enabling the electric utility to eliminate all useless duplication of circuits and equipment, obtain a broader use of privately owned plant, and retire investment in such plant in an orderly fashion.

In some companies the responsibility for adequate and satisfactory communication service throughout the entire system has been centralized in one department. This department gives specialized, continuous attention to the needs of the utility for communication. Where such a plan is in effect, it is important that the department be fully conversant with the general overall objectives of the company and have sufficient authority to initiate such action as may be necessary to provide communication service which will be of the greatest assistance in meeting those objectives.

ESTABLISHMENT OF BASIC PLAN

The data obtained by analyzing the communication service required in connection with the various activities of an electric utility, as outlined in previous sections of this paper, provide the material for the preparation of a basic communication plan.

The establishment of such a plan requires the exercise of judgment to evaluate the relative importance of the various activities of the utility and the extent to which available communication services and facilities can be used practicably to expedite such activities. The value of the plan adopted will depend upon the quality of judgment exercised. It is extremely important, therefore, that the best available knowledge and experience in the power and communication field be enlisted in establishing a basic plan.

The establishment of a basic plan and its specific application will necessitate periodical reviews of existing communication arrangements to insure that the plan is being followed. Modification of the plan itself may also be necessary from time to time on account of new developments, changes in operating practises, etc.

APPLICATION OF BASIC PLAN

The specific form and detailed application of a basic communication plan for an electric utility is dependent upon local conditions and is therefore outside the scope of this paper. Information in regard to the specific communication facilities used by electric utilities in meeting their requirements has been given in a number of important papers recently presented before the Institute. The contents of these papers are briefly summarized in the attached bibliography. Also, further information regarding the communication arrangements in a number of interesting and important cases involving widely different operating requirements is given in the other papers of this symposium.

The growth of the electric utility industry is extremely rapid. The activities of the operating companies are continually broadening in scope as the areas served increase in size and the customers' demands become heavier and more exacting. It is clear that adequate, convenient communication service cannot be obtained by the electric utility economically without a plan based on a thorough knowledge of requirements and the availability of various communication service and facilities to meet those requirements. It is important that the activities of the electric utility be constantly studied from a communication standpoint to determine how communication can be used to greater advantage, and to anticipate requirements so that the communication service necessary will be available on the date required. Consideration along these lines will assist to a marked degree in effecting continual improvement in customer service.

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A description of carrier-current communication over a 132-kv. network having an extent of 2,500 linear miles is given. The necessity for zoning and inter-zoning is brought out. Data are cited as to cost, maintenance, reliability, traffic, and safety. The fundamentals of power line carrier-current communication over a transmission network are summarized and the need for certain development work outlined.

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The experience of the Alabama Power Company with power line carrier-current telephony and supervisory control is outlined. The early development of these systems in the Alabama Power Company's territory is discussed as well as systems later installed. Extracts are given from the general specifications for the equipment used.

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This paper gives a brief outline of the electric utility's requirements for power line carrier-current communication, the problems involved in furnishing such communication and briefly describes the different types of equipment available.

Problems in Power Line Carrier Telephony and Recent Developments to Meet Them, by W. V. Wolfe and J. D. Sarros, A. I. E. E. Trans., Volume 48, p. 107.

The problem of applying high frequency communication to power systems is outlined in this paper. The effects of branch lines and switches in the power system network and sources of noise in the carrier-current channel from operation of the power circuits are discussed. Methods of obtaining simplex and duplex operation of carrier systems as well as carrier and side-band suppression are outlined briefly. A brief description is included of a single frequency, single side-band, carrier suppressed type of power line carrier-current communication system.

Transmission of High Frequency Currents for Communication Over Existing Power Networks, by C. A. Boddie and R. C. Curtis, A. I. E. E. Trans., Volume 48, p. 227.

The fact that carrier-current communication presents certain difficulties not encountered in other types of communication channels is brought out in this paper, which describes the use of tuned choke coils to isolate the power line carrier-current communication channels from the remainder of the power system. It is stated that this gives in effect a simple communication circuit between communicating points.

Telemetering and Supervisory Control

Telemetering, by C. H. Linder, C. E. Stewart, H. B. Rex and A. S. Fitzgerald, A. I. E. E. Trans., Volume 48, p. 766.

Operating requirements and channels available for the transmission of meter readings are discussed. The field of application for telemetering is surveyed and discussed in its relation to supervisory control. The installation of a specific type of telemetering is described.

Development of a Two-Wire Supervisory Control System with Remote Metering, by R. J. Wensley and W. M. Donovon, A. I. E. E. Trans., Volume 49, p. 1339.

The conditions leading up to the development of a two-wire supervisory control system are described. The paper enumerates the outstanding requirements of supervisory control systems in general and indicates the advantages of a two-wire system. The operation of the two-wire system is briefly described.

An Electron Tube Telemetering System, by A. S. Fitzgerald, A. I. E. E. Trans., Volume 49, p. 1321.

The paper describes a varying frequency telemetering system which employs an electron tube, beat frequency oscillator. A method of furnishing a number of telemetering indications over a single conducting channel by the use of automatic telephone type selectors at transmitting and receiving stations, is described.

A thyratron circuit is described, by means of which a number of varying frequency telemetering signals may be totalized.

Centralized Control of System Operation, by James T. Lawson, A. I. E. E. Trans., Volume 49, p. 1344.

Centralized control of system operation of the Public Service Electric & Gas Company of New Jersey is described. Detailed descriptions are included of the power and telephone apparatus installed and the methods used to provide indications of the operation of electrical apparatus. The results obtained by means of centralized control are described.

Discussion

Howard S. Phelps: With the present tendencies toward system expansion, either through ownership control or operating agreements between companies in adjacent areas, there are two items that should be given particular attention when making fundamental studies of communication services of electric utilities which it seems to me the authors of this paper have not particularly stressed.

The first of these is the quality of voice transmission that will be provided for on that part of the system devoted to the use of the system load dispatchers. This is essential to insure as far as possible against misunderstanding of operating instructions. For this service the quality of transmission should undoubtedly be at least the equal of that for high-grade commercial telephone communication.

The second item is that factor in voice communication generally spoken of as "transmission margin" which means the amount by which a given volume of voice transmission, irrespective of quality, can be decreased to a point where transmission is just intelligible. Undoubtedly, in general, it would be good engineering to provide for considerable transmission margin in order to assure that satisfactory voice communication is available as the system may expand or in the event it is necessary to reroute communication circuits following storm or other trouble that may occur on the communication lines.

Any company that is seriously considering the installation of a new communication system, or revamping its present system, certainly should give detailed attention to the two factors in voice communication to which reference has just been made. An ill-advised attempt to save money through the installation of fair quality transmitting and receiving sets, or the installation of the minimum size of wire in the communication system, or both, might easily impose a very serious burden on the future communication services to be rendered.

International Standard of Electromotive Force
and Its Low-Temperature-Coefficient Form

BY MARION EPPLEY*
Member, A. I. E. E.

"THE electromagnetic unit e. m. f. exists between two points when one erg of work is done by one electromagnetic unit of current flowing for one second between the two points."[1]

"Unit current is the current which, flowing through a circle of one centimeter radius in air, exerts a force of 2 π dynes on a unit magnetic pole at the center of the circle."[2]

"The c. g. s. electrostatic unit difference of potential exists between two points when one erg of work is done in the movement of a c. g. s. electrostatic unit of charge from the one point to the other point."[3]

The above definitions are fundamental but it is not simple to give being to the physical conditions for which they call.

Even the international volt ("the electrical pressure which when steadily applied to a conductor the resistance of which is one international ohm will produce a current of one international ampere")[4] is defined actually in terms of the silver voltameter and the mercury ohm. This combination does not lend itself to routine measurements, even though the mercury ohm can have substituted for it a wire resistance-standard. Moreover, the voltameter measures the total quantity of electricity (the number of coulombs) that pass through it. This total, divided by the time of passage in seconds, gives the *average* current in amperes, so that only steady electromotive forces can be determined by the voltameter with the ohm, unless the accuracy of the results be vitiated by this integrating effect. Hence, to have determinations of electromotive force in the sense of the above definition give definite meaning with respect to voltage, it is essential to have an outside source of constant potential difference by means of which an unchanging drop in the voltameter circuit can be maintained. Up to the present time the most precise and the most convenient method of producing a steady potential difference with the required precision is by means of a galvanic cell of the proper characteristics. When an element with a constant electromotive force has been used once so to maintain the voltameter circuit with a steady drop across the standard ohm, equal to the e. m. f. of the cell, this last obviously has been calibrated in terms of the international volt, and its independent use as a standard immediately is possible.

Elements so used are called "standard cells." They must be constant in electromotive force, or at the worst their electromotive forces should change slowly and regularly with time. Their temperature-coefficient should be such that a variation of ± 0.01 deg. cent. in the neighborhood of 25 deg. cent. causes a change in e. m. f. of less than one microvolt, and they should exhibit no effects due to temperature-hysteresis greater than this for a like temperature change. They should be reproducible as to e. m. f., but this is a matter of convenience only, since calibration with the voltameter and the ohm could be practised upon every cell used as a primary standard.

The container of a standard cell should be of such a design that concentration effects at the electrode faces are eliminated. That is, a more concentrated, heavier solution must not be able to flow, under the action of gravity, to one electrode and not to the other. Also the path between the electrodes should be as long as is consistent with low internal resistance, since the two electrode systems, by the very nature of things, are not in equilibrium with each other. For this reason, the diffusion from one to the other of ions that interact is to be hindered as much as possible. These two conditions are fulfilled by the "H-tube" due to Rayleigh which is in general use. Other forms have been proposed, notably a pair of concentric cylinders,[5] the inner cylinder, and the annular space between the inner cylinder and the outer one holding the two electrodes. This receptacle offers certain difficulties in glass-blowing, and its main advantage, uniformity of temperature of the two electrodes, can be secured more readily by other means.

From the standpoint of handling there are two types of cell, the portable and the non-portable. Portability is secured by some form of septum inserted in each leg of the cell vessel to hold the solid constituents in place. This can be a perforated cork disk covered with silk or linen, a porous stopper of porcelain wrapped with some sort of fiber, or any similar mechanical device. Non-portable cells have no septa, and must be held in a vertical position to prevent mixing of their contents.

Laboratory standards certified to 0.01 per cent should be portable; primary standards, reproducible to five to ten microvolts, should be non-portable, since septa introduce another factor in the system of primary standards. This is not to be desired. (The specific values above apply to the cell in general use today.)

From the physical-chemical standpoint (which involves behavior) there are also two types, the saturated or normal cell, and the unsaturated cell. The saturated or normal cell has an excess of a salt of the metal of each

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*Eppley Research Laboratory, Newport, R. I.

1. For references see end of paper.

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electrode. In practise, the two salts have the same acid radicle. The solid of the salt of the less electropositive metal is in the vicinity of its electrode only. It should not be too soluble, or diffusion to the opposite pole will be too rapid. The solid of the salt of the more electropositive metal can be in the vicinity of both electrodes. The unsaturated cell has no solid phase of the salt of the more electropositive metal, its electrolyte being saturated with this at some temperature well below the lowest probable room temperature. Owing to the excess of the salts of both metals in the normal cell, the electrolyte becomes saturated with these, when maintained for a proper length of time at any temperature within the useful range of the cell, to the concentration corresponding to the particular temperature. Since the e. m. f. is a function of these concentrations, saturated cells are reproducible in so far as their e. m. f. depends upon concentration. Because of the difficulty of bringing once and for all a solution to a single predetermined degree of saturation, unsaturated cells are not reproducible, strictly speaking.

Unsaturated cells have a lower temperature-coefficient than saturated cells. Therefore, laboratory standards should be of the unsaturated type, exposed as they are to changes or room temperature. Primary standards, in which reproducibility is so convenient as to be an essential, should be saturated cells. They must be maintained at constant temperature in a thermostat. Laboratory or secondary standards are calibrated in terms of these primary standards.

A number of systems has been proposed for the purpose under discussion, and some of these made use of in default of something better, but all except one are of historic interest only. This one, the combination upon which are based the primary and the secondary standards of the present period is the following: mercury—mercurous sulfate—aqueous solution of cadmium sulfate—cadmium amalgam.

It was proposed by Dr. Edward Weston, and its unsaturated type patented by him in 1893. To Dr. Weston belongs great credit for the long step forward made by his introduction of a standard of electromotive force with a low-temperature-coefficient (negligible for all practical purposes) and in addition free from the mechanical instabilities of the Clark and Clark-Carhart cells which were its predecessors.[6]

In his honor, the two types of this cell are known as the normal Weston cell or the saturated Weston cell, and as the unsaturated Weston cell or simply the Weston cell. The word cadmium is quite as often used as the word Weston and instead of it, cadmium cell and Weston cell being synonymous as applied to the composition of the *system*, but Weston cell requiring no further qualification to denote it refers to an *unsaturated* element.

Cadmium sulfate ($CdSO_4 . 8/3H_2O$) is a well defined salt. It can be secured readily as clear crystals by spontaneous crystallization. Hulett[7] states that it does not seem to be isomorphous with any known salt. However, an unfinished investigation in this laboratory, has shown even clear, once re-crystallized crystals of high-grade commercial salt, after twelve washings, to have contained appreciable quantities of manganese. Also, crystals can be prepared which contain a considerable proportion of mercuric mercury. Iron too appears to be present in clear crystals in a closely-bound state at times. The mercuric mercury is no doubt present in such form as to produce a mixed-crystal rather than a double salt, though the final proof of this is still to be made. The same is no doubt true of manganese and iron. The author has found no mention in the literature of manganese as an impurity in cadmium sulfate other than a statement made by him in 1926.[8] The impurities usually listed[9] as probable are zinc, lead, ferrous, and ferric iron and occasionally nickel. A rather wide review of the literature plus chemical checks in this laboratory make it appear reasonably certain that too much faith has been placed by investigators in the effectiveness of the simple methods used to purify the cadmium sulfate used by them in standard cells, and that manganese, which the author has found in a wide range of cadmium sulfates tested, may have been present in most cases. Also iron.

Qualitative experiments made by us as far back as 1924[10] showed manganese to cause higher initial electromotive forces when present as an impurity in cells than were found when its concentration was reduced to very low limits. These higher electromotive forces did not remain constant.

Through the courtesy of the Bureau of Standards a sample of the cadmium sulfate prepared by Wolff and Waters[11] in 1906 has been received recently for investigation. This salt, with which, it is understood, the fundamental standards of the United States were set up, gives a negative test for manganese. The excellence of these standards has been proven by time.

While the case against manganese by no means has been proved, it would be safest, until it has been found to have no injurious effects, to specify its elimination in primary standards, and its reduction to low limits in other cells.

A low manganese content is secured with no great difficulty. Its elimination requires no small degree of care. A method, soon to be described, has been developed by the author, but it is so far from convenient for the preparation of large quantities of the salt, that a simpler one is being sought.

The preparation of mercury that gives the desired results presents no difficulty. It is washed in a fine spray in dilute nitric acid,[12] and is distilled in a partial vacuum. The tendency to "bump" is prevented by passing a slow current of air into the mercury through a capillary. This also serves to oxidize the base metals. The noble metals remain behind in the residue.[13]

Cadmium can be purchased in the metallic form in a satisfactory state of purity. However, only one such source seems to be available for a routine supply. Cadmium sulfate can be used as a source of cadmium as will be mentioned in the next paragraph.

As has already been indicated, leaving out of consideration the solid cadmium sulfate, one pole of the Weston system consists of mercury, covered with mercurous sulfate, and the other of cadmium amalgam. The cadmium amalgam to give a smooth temperature-electromotive force curve must consist of two phases, a solid phase which is a solid solution of cadmium in mercury and a liquid phase which is a saturated solution of the solid in mercury.[14] Within the temperatures between 15 deg. cent. and 40 deg. cent. amalgams of about 8 to 13 per cent[15] cadmium are satisfactory. There seems to be cause of irregularity at 15 deg. cent. (about) which may interfere with accurate measurements below this point. The amalgam can be made by dissolving the correct weight of cadmium in mercury, or by electrolyzing the cadmium from an appropriate weight of cadmium sulfate into mercury.

Mercurous sulfate plays an important role in the Weston cell, so important in fact that it is customary to charge all irregularities in cells to it. The salt is sensitive to many conditions, one of which, at least, makes it useful as a "depolarizer." This is its ready reducibility, which prevents cadmium ion from entering the mercury electrode. It is also sensitive to light, and should be protected from this, since it causes a decomposition which is injurious to the constancy of cells. It also hydrolyses[16] in neutral or very slightly acid cadmium sulfate solution, hence the electrolyte should be somewhat acid. The hydrolysed salt is a very pale green,[17] not yellow as sometimes stated in the older literature. The salt, when exposed to oxygen can form a yellow basic mercuric salt of low solubility.[18] This basic mercuric sulfate seems to be reduced to the normal mercurous salt in the presence of sulfuric acid in cadmium sulfate solution, and mercury.[19] This basic mercuric salt forms only as a coating[20] on the grains of the normal mercurous sulfate and protects them against further oxidation, it would appear, and in a slightly acid solution of cadmium sulfate is dissolved and reduced by the mercury of the cell. The solubility in acid solutions of cadmium sulfate has been determined to be considerable by experiments completed last year and as yet unpublished.

The mercury limb of a cell has been rotated by Hulett,[21] and the e. m. f. determined against an amalgam electrode which could be connected with it when desired. Upon rotation the e. m. f. rose to about 1.02 volt, but fell upon standing still. The author has repeated Hulett's experiments, in a slightly different form, with practically complete agreement with his results. Wolff and Waters[22] rotated the cathode of a cadmium cell, but found no variation of e. m. f. greater than 0.01 per cent. It has not been possible to reconcile the results of these investigators as yet, but one thing may be said with confidence, namely that at the mercury face the system is in equilibrium. It is at this face that the potential difference due to the mercury electrode has its being.

Mercurous sulfate can be made by a number of methods,[23] but that prepared by electrolysis is undoubtedly the best. The gray electrolytic salt, deriving its color from small globules of mercury gives better results than a white salt.

Since current should not be drawn from a cell, cells should be used only in a "null-point" or compensation method. Some form of potentiometer provides this. It is usual to compare the entire electromotive force of the cell used as standard against the entire e. m. f. of the cell the electromotive force of which is to be determined. In this method the drop in the potentiometer acts as a transfer standard. It is essential that this drop be kept constant, so that it is well to lag the storage cell with heat-insulating material to prevent changes in room temperature from causing fluctuations in the measuring current, or drop. Accumulators are best kept on a stand, above the floor, to avoid drafts. With this precaution, and that of shifting from standard to unknown several times with readjustment of the measuring current if necessary and the attainment of a new balance with the unknown, results can be obtained with a potentiometer of proper design that will be reproducible from day to day within six microvolts. This method has the convenience of being direct reading.

But the above method has the disadvantage, perhaps more theoretical than real, of not comparing the standard and the unknown at the same instant. For measurements beyond criticism, therefore, it is best to oppose the unknown and the standard, reading the residual e. m. f. on a potentiometer or by some other suitable means. This reduces the effect of fluctuations in the measuring current to a minimum and makes use of only one or two dials of the potentiometer with reduction in the number of corrections to be applied. It is not direct reading, however, and the sign of the residual must be watched carefully.

It is necessary of course that the measuring current be allowed to flow for a long enough time before measurements are made for it to have come to a steady state, whatever method be used. Careful attention should also be given to shielding the installation against stray leakage currents.[24]

In any system, provision should be made to eliminate the effect of thermoelectric forces. A very excellent method has been proposed by the Bureau of Standards. It is an adaptation, for standard cell comparisons, of the assemblage of Lindeck and Rothe,[25] with new and useful features.

It is made clear by the diagram herewith. (Fig. 1.) This assemblage consists of a standard resistance of appropriate value, R_s. This is in series on the one hand with a reversing switch, an ammeter A, a battery and a rheostat, indicated as circuit I. In an opposed branch circuit there are a standard cell S, the unknown electromotive force X differing but slightly from that of the standard cell, and a galvanometer G. Means are provided for disconnecting the standard cell and the unknown and replacing them with a neutral resistance R_c about equal to their combined resistances. There is also a resistance, R_t, in this circuit. This entire branch is marked circuit II.

Across the resistance R_t there are connected through a pole-changing switch an ammeter (for convenience), a battery, and a rheostat. This is marked circuit III.

The purpose of this assemblage is to permit the difference of electromotive force which is being compensated to be thrown out of the circuit at the same time that the current in the side branch I is interrupted. In order to keep the galvanometer damping the same, the resistance R_c is substituted for that of the standard and the unknown. Then by means of the branch circuit III the parasitic thermal electromotive forces that may exist in circuit II are compensated by the battery and rheostat in side circuit III. Then the resistance R_c is thrown out, and the standard cell and the unknown electromotive force "bucking" it, opposed to the side circuit I, are thrown into action and a balance obtained. In this way it is possible to get a difference reading between S and X with parasitic electromotive forces eliminated.

The diagram with values inserted as shown in (Fig. 2) is the form in which the principle is used in this laboratory. It gives the desired flexibility. No explanation of the details is necessary.

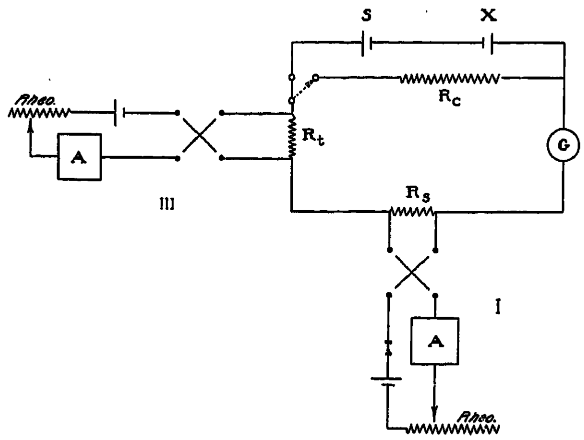

FIG. 1—OPPOSITION METHOD

As suggested by Bureau of Standards

The London International Electrical Congress[26] in 1908 adopted specifications for the mercury ohm; the silver voltameter, and the Weston normal cell, fixing a provisional value of 1.0184 international volts at 20 deg. cent. for this latter.

The value of 1.0184 was chosen because it was the mean of the figure 1.01843 obtained at the National Physical Laboratory in 1906-7, and the figure 1.01834 obtained at the Reichsanstalt in 1907-8. Both of these values were based on an electrochemical equivalent of silver equaling 1.11800 mg. per coulomb.

The specifications for the mercury ohm and the Weston cell were fairly complete, but those for the silver voltameter were inadequate, hence the above value for the cell was adopted as provisional only, until more precise values should have been determined by further experiments.[27]

For the encouragement of such experiments, and to promote the cooperation of the different countries throughout the world in maintaining a single uniform system of electrical units, the London Conference established an International Committee on Electrical Units and Standards.

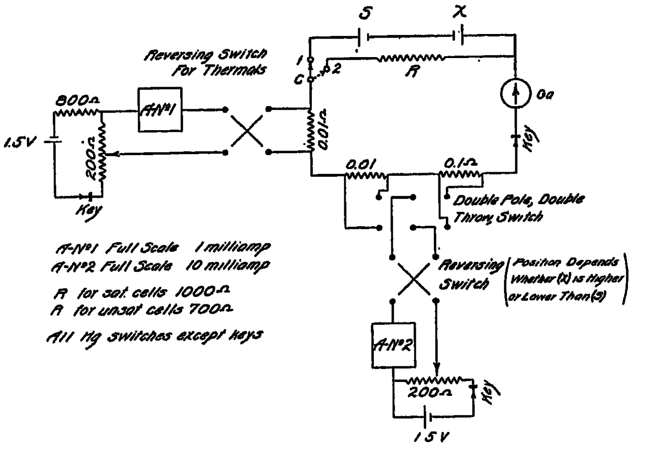
S
X
Reversing Switch For Thermals
1
2
C
R
Ga
800Ω
A-Nº1
1.5V
200Ω
0.01Ω
Key
Key
0.01
0.1Ω
Double Pole, Double Throw Switch
A-Nº1 Full Scale 1 milliamp
A-Nº2 Full Scale 10 milliamp
R for sat. cells 1000Ω
R for unsat cells 700Ω
All Hg switches except keys
Reversing Switch
(Position Depends Whether (X) is Higher or Lower Than (S))
A-Nº2
200Ω
Key
1.5V

FIG. 2—OPPOSITION METHOD

Modified form, The Eppley Laboratory

On March 1, 1909 the acknowledged figures for the value of the normal Weston cell at 20 deg. cent., obtained by means of the silver voltameter, using 1.11800 mg. per coulombs as the electrochemical equivalent of silver were as follows:

At Nat. Phys. Lab., using filter paper	1.01843 volts at 20 deg. cent.
At Phys.-Tech. Reichs., using silk and porous cups	1.01834 volts at 20 deg. cent.
At Bur. of Stands., using porous cups	1.01837 volts at 20 deg. cent.
At Bur. of Stands., using filter paper	1.01863 volts at 20 deg. cent.
At Lab. Cen. d'Elec., using filter paper	1.01879 volts at 20 deg. cent.

In view of the wide spread in these values, delegates from the several national standardizing laboratories met in Washington on April 4, 1910. This body was known as the International Technical Committee, and was brought into being through the initiative of Dr. S. W. Stratton, Director of the Bureau of Standards. One-quarter of the traveling expenses of the delegates was defrayed by the American Institute of Electrical Engineers.

The delegates[28] made determinations with the silver voltameter, and set up and compared normal Weston cells; forty-eight cells were made by them in Washington, using four different preparations of mercurous sulfate. In addition 15 cells were brought over and submitted from the PTR, 34 from the NPL, 15 from the LCE and 7 cells were chosen as representative of the standards of the Bureau of Standards in addition to forty new cells submitted by it.

The agreement of the cells submitted is given in the next table:

Cells		Mean of group minus general mean; difference in 10^{-6}	Average deviation of single cells from mean of group
No.	Laboratory		
15	PTR	0	±10
34	NPL	−2	± 9
15	LCE	+9	±25
40	NBS	−9	± 6

The group means for the new cells set up in Washington by the delegates [Twelve cells each. Four groups of three cells, the groups being made with one of the preparations of mercurous sulfate made by each delegate according to the method of his own national laboratory] are listed in the following table:

Hg_2SO_4	Set up by				Mean omitting LCE
	NBS	LCE	NPL	PTR	
NBS	−17	+147	−29	−34	−27
LCE	+19	+62	+18	+15	+17
NPL	−35	+142	−12	−17	−21
PTR	+11	+121	+3	+19	+11
Means	−6	+118	−5	−4	−5

The LCE cells were set up under conditions, due to interruptions that made their proper agreement a practical impossibility.[29]

As a result of the work done by it in Washington The Technical Committee decided "to recommend to the International Committee for Electrical Units and Standards the following value for the e. m. f. of the Weston normal cell:

$E = 1.0183$ international volts at 20 deg. cent."[30]

Upon submission of a proposal to do so and acceptance by it of the proposal, the International Committee requested the governments involved to adopt officially the new value for the Weston normal cell on January 1, 1911.

In the case of the Bureau of Standards no legislation was necessary to make the new value effective, so the Bureau adopted it in advance of legislative action, on the first of January 1911, carrying it out one more decimal place to 1.01830.

It also accepted the temperature coefficient formula of the Weston normal cell of the London Conference, namely,

$$E_t = E_{20} - 0.0000406\ (t-20) - 0.00000095\ (t-20)^2 + 0.00000001\ (t-20)^3$$

The values for the normal Weston cell in use previous to 1911 are of interest. They are

In the United States	1.0189	international	volts	at	25	deg.
equivalent to	1.019126	"	"	"	20	"
In Germany	1.0186	"	"	"	20	"
In Great Britain	1.0184	"	"	"	20	"

(Great Britain, until January 1, 1909, when the value 1.0184 adopted provisionally by the London Conference was adopted provisionally by the NPL, used a value slightly larger than that of the United States.)[31]

It should be noted that the electromotive force of a normal cell depends upon temperature not only as concerns the system's correspondence to the equilibrium conditions at a temperature, but also to the actual value of the particular temperature on a definite scale. The first condition is a function of the closeness with which the temperature is controlled; the second is met by determining the temperature and its fluctuations with the platinum resistance thermometer by which the International Temperature Scale is defined.[32] A tenth of a degree error in temperature causes about 5 microvolts error in e. m. f. at 25 deg. The error caused by fluctuations through a temperature range of one-tenth degree may cause an error twice as great as this in some cells, due to hysteresis.

The cause of hysteresis is not thoroughly understood. It has been explained as due to a shift in the mercurous-mercuric ion equilibrium with temperature,[33] and also to supersaturation of the viscous cadmium sulfate solution with mercurous sulfate.[34] It is less when the temperature is raised than when the temperature is lowered. Acid in the electrolyte reduces hysteresis to a low value. So does finely divided mercury in the mercurous sulfate. It probably cannot be explained by a single, simple cause. For some reason it is greater in portable cells than in non-portable, and greatest in neutral, normal, portable cells with their solid cadmium sulfate.

At the Bureau of Standards normal cells are maintained to within 0.01 deg. cent. or better in electrically-heated oil baths. These baths are not lagged with heat-insulating material, as it is not wished to have the bath temperature rise over night sufficiently to "cook" the cells in case of mal-functioning of the regulating device. A cooling system for the room as a whole is provided for use in hot weather. This is a much better plan than that of endeavoring to regulate the baths by a constant abstraction of heat from them by a cooling coil in the oil when room temperature is higher than the bath temperature. Temperatures are determined by means of platinum resistance thermometers and the Mueller temperature bridge. (The main coils of the bridge are at constant temperature in one of the thermostats, and only the very small resistance made up of low-resistance coils, necessary to balance the slight changes of thermometer resistance, are at room temperature.)

Comparisons of electromotive force are made by the difference method with the old type of Feussner potentiometer constructed by Otto Wolff. This instrument has been calibrated with great care. It is understood that an arrangement to compensate for parasitic thermals has been installed or is about to be installed for use with the Wolff potentiometer though no thermals are evident. All wiring is installed with especial regard to the elimination of thermals, and "shielding" is carefully attended to.

In this laboratory, the installation is essentially the same as that at the Bureau except that the baths, two in number are heavily lagged, and no part of the metal of the bath in contact with the heated oil projects into the room, except the stirrer shaft. One bath is nearly twice the size of those in the Bureau and holds one hundred cells. A special type of potentiometer reading to ten microvolts, and an improved Feussner potentiometer, both direct reading, are used for comparing the entire e. m. f. of the unknown with that of the standard. Accumulators furnishing the measuring current are lagged against temperature changes and are off the floor. Difference measurements can be made by the assemblage described above and by a White potentiometer reading to microvolts. Temperatures are measured by the platinum resistance thermometer and a modified type of Mueller bridge, oil immersed with temperature control. No cooling system for the room has been installed as yet, as the room is not expected to heat up in summer, due to its position and on the basis of experience with smaller baths maintained in it in the past. The present baths have not been in operation throughout a summer. Regulation of temperature is within 0.01 deg. cent.

There can be no greater authority upon the maintenance of the volt than G. W. Vinal, physicist, charged with this important duty at the Bureau of Standards. There is spread below verbatim an extract from an article by him upon this subject.[35]

MAINTENANCE OF THE STANDARD

Between 1910 and 1912 our basis of reference was the group of 36 cells, left at the Bureau after the departure of the delegates. It became evident, however, that many of our cells, which had shown consistent values on the old basis of reference, were gradually increasing in value on this new basis as represented by the 36 cells which the technical committee left at the Bureau. All the evidence pointed to the fact that the mean of these 36 cells was decreasing, and it was then decided that a group of 19 selected cells, which had shown a satisfactory degree of constancy before 1910, and which had shown nearly equal increases in value in terms of the new basis of reference, had actually remained constant. These cells were then selected as a new reference group.

TABLE I—VALUE OF THE REFERENCE CELL IN TERMS OF THE PRIMARY REFERENCE GROUP

Date	Difference in microvolts from mean of group
Oct. 3, 1924	–6.9
July 15, 1925	–6.9
Nov. 17, 1925	–7.6
May 1, 1926	–7.8
Nov. 4, 1926	–6.5
Apr. 21, 1927	–8.1
Nov. 5, 1927	–5.8
June 5, 1928	–5.7

Some substitutions have been made in this group between 1912 and 1919, but no change has been made since 1919. The primary reference group (Group I) at the present time consists of 20 cells, 15 of which were made 22 years ago by F. A. Wolff and C. E. Waters. These cells have shown a remarkable degree of constancy, and no correction for any yearly decrease in voltage is made. Table I shows values of the reference cell, which is one cell of the group in daily use during the last four years. The maximum variation is only a few microvolts.

To safeguard the unit and at the same time provide further information as to the constancy of these cells, in 1925 two secondary reference groups of 10 cells each (Groups II and III) were selected from the Bureau's stock of seasoned cells. One of these groups is kept in the safe in the south building of the Bureau with the national prototype kilogram and meter, and the other secondary group is kept in the safe in the electrical building. The secondary groups are compared with the primary group about once in six months. The values are given in Table II. The maximum variation in each group is four and six microvolts respectively.

TABLE II—SUPPLEMENTARY REFERENCE GROUPS IN TERMS OF PRIMARY REFERENCE GROUPS

Date	Difference in microvolts from mean of Group I	
	Group II	Group III
Jan. 8, 1925	–1.9	–16.3
Feb. 16, 1925	–3.1	–17.3
May 26, 1925		–15.9
Nov. 18, 1925	–5.4	–20.8*
May 17, 1926	–1.7	
June 1, 1926		–22.9
Dec. 18, 1926		–24.0
Jan. 11, 1927	–3.0	
July 22, 1927	†	–26.8
April 17, 1928	–2.8	–25.9

*Three cells were changed in Group III prior to this measurement.
†One cell in Group II was found to be broken and it was replaced at this time.

INTERNATIONAL COMPARISONS

At the British National Laboratory the standard for voltage is maintained in quite a different way. Groups of new cells are set up annually, and the basis of reference is the average of the cells for the preceding three years.

Recent comparisons of the Bureau's basis of reference with that of the British Laboratory have indicated that the difference between our value for the volt and theirs is about one part in 100,000. Confirmation of this has been received through a report from the Central Chamber of Weights and Measures at Leningrad, indicating a difference between the above standards of seven millionths of a volt.

The value for the volt which was presumably the same in the various countries on January 1, 1911, has not remained the same in all countries, however, as shown by Fig. 3, which is based partly upon a report of the Chamber of Weights and Measures at Leningrad, and partly upon the exchange of cells between the Bureau of Standards and National Laboratories of other countries. The fact that the value for the volt as defined by the Weston cell in several countries differs so widely cannot be interpreted, however, as meaning that the cell is an unreliable standard, since these values involve not only errors in the cell, but the errors in the standards of resistance and the measurement of current. This lack of uniformity is not surprising in view of the fact that no adequate international specifications for either the standard cell or the voltameter have been adopted.

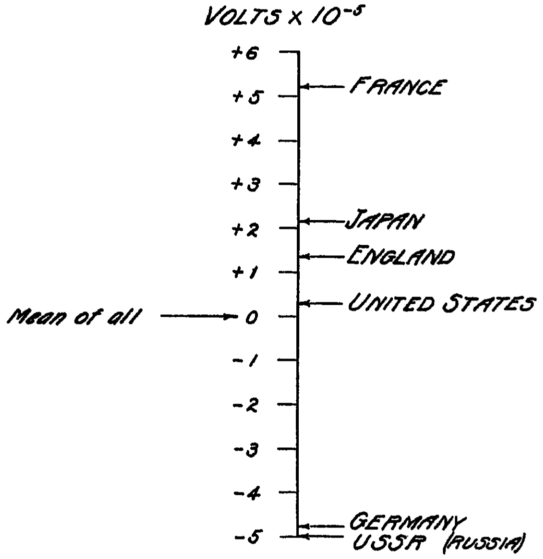

FIG. 3—RELATIVE VALUE OF THE VOLT AT THE PRESENT TIME IN SIX COUNTRIES

Vinal, *Trans. Am. Electrochemical Society*, 54, 251 (1928) Fig. 1

Five determinations with the Smith form of voltameter reported in the above article, gave a mean for the value of the normal Weston cell of 1.018307. Six determinations with the Richards or porous cup form of voltameter gave a mean of 1.018218. Even this last value, which is lower than any obtained during the investigation of 1908, and therefore probably put in error by some interfering factor, is low by 0.01 per cent only.[36]

The cells just discussed are the normal higher temperature-coefficient type. The unsaturated type or Weston cell now becomes of interest. As said before this is not strictly reproducible, but its voltage can be made to fall within narrow limits, and the cell can be standardized by comparison with a normal cell since its e. m. f. is to all intents constant.[37]

Vosburgh and Eppley found in a series of forty-five Weston cells that the electromotive force increased in an approximately linear manner as the cadmium sulfate concentration decreased. The e. m. f. ran from 1.018270 volts for 43.22 per cent $CdSO_4$ to 1.02095 volts for 41.84 per cent $CdSO_4$.

The electromotive forces of these cells were linear functions of the temperature between 15 deg. and 35 deg. cent., but were not linear functions between 35 deg. and 45 deg. cent.

The temperature coefficient between 15 deg. cent. and 35 deg. cent. was a function of the electromotive force. It decreased from 0.0000028 volts per degree for cells with an electromotive force of 1.01827 volts to − 0.000013 volts per degree for cells with an electromotive force of 1.0210 volts, being zero for a cell with an electromotive force of 1.01873 volts.

These cells contained approximately 0.0115 moles of sulfuric acid per liter. The cell with zero temperature coefficient would be saturated at 4 deg. cent., if the effect of sulfuric acid on the solubility of cadmium sulfate is the same at lower temperatures as between 15 and 20 deg.

Three groups of portable cells, each group having a different form of construction, have just been investigated for temperature coefficient and hysteresis in this laboratory. They were maintained until the cells were constant to within 10 microvolts (about), except at 45 deg. and 50 deg., at each of the temperatures shown below, and their e. m. f. determined each day. The mean of the readings on the last two days was taken as the e. m. f. at equilibrium, but any reading for a particular temperature could have been taken as such without error greater than 0.01 per cent. Temperature control was within ± 0.02 deg. cent.

The temperatures and the temperature coefficients for the corresponding intervals, together with the acidities of the electrolytes of the cells with respect to sulfuric acid are given in the table herewith.

Temperature interval	Temperature coefficient microvolts per 1 deg. cent.		
	1st group def. 0.04 N	2nd group pre. 0.04 N	3rd group pyr. 0.03 N
15°.04–20°.00	−3.70	−2.86	−4.59
20°.00–25°.08	−2.80	−2.85	−3.09
25°.08–30°.04	−4.03	−2.72	−2.72
30°.04–35°.02	−5.64	−4.67	−7.38
35°.02–40°.11	−1.37	− .74	−1.37
40°.11–45°.38	−1.78	+9.27	−1.53
45°.38–50°.04	+1.86	−8.45	+3.54

After measurements were completed on this rising temperature cycle, a cycle was run through with the same temperatures in the reverse order. This cycle is not yet completed for 20 deg. and 15 deg. However, as far as it has been carried, the results are in agreement with the first cycle to within 0.008 per cent in the worst case. Equilibrium was slower, as has been so often noted, on the downward cycle.

The three groups after having been at equilibrium at 30 deg. on the downward cycle were suddenly cooled to 25 deg. They were measured at this new temperature seventy minutes on the average after having been cooled to it. Cooling from 30 to 25 deg. required about 20 minutes. The average of the e. m. f. of two of the groups was within 0.02 per cent of the average of their values at 25 deg. taken before the test began. The average of the other group was within 0.027 per cent of its corresponding value.

Unsaturated cells show a downward drift with time.

In this connection the Bureau[38] of Standards has the following to say of the Weston cells in its laboratories in 1910. "The electromotive force of these cells generally decreases slightly with age. To illustrate, the Bureau of Standards has 15 of these cells in use in its laboratories which have on the average decreased only one ten-thousandth of a volt in the last four years, the change in the various cells being from nothing to three ten-thousandths of a volt." That is, the average in per cent was very nearly 0.01 per cent for four years or 0.003 per cent per annum, and the maximum 0.008 per cent per annum, very closely. These values are in close agreement with the values for this decrease found in this laboratory, 0.003 per cent to 0.004 per cent per annum.[39] This slow decrease can be well explained by the diffusion of mercurous ion to the amalgam face and its discharge there with cadmium going into solution and increasing the cadmium concentration of the electrolyte. The drop due to this cause should cease when the e. m. f. of a saturated cell is reached. Another more rapid drop is often observed in unreliable cells, and is beyond doubt caused by hydrolysis. This does not stop at the value of the saturated cell. Such cells in practically every case—certainly in every case observed—have shown large hysteresis effects. They should be discarded. Hence, for an accuracy of 0.01 per cent unsaturated cells should be recertified every two years, and in addition, when in use they should be maintained within 5 deg. cent. of the temperature for which the certified value is given.

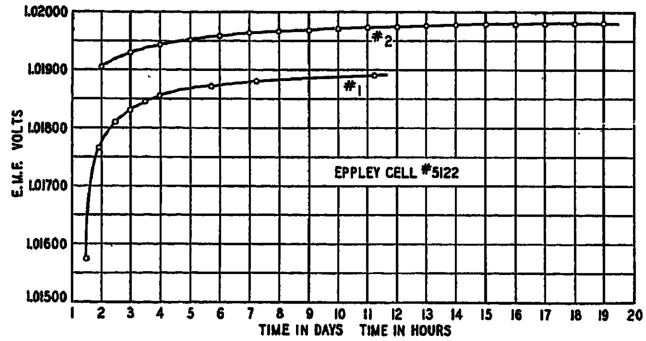

FIG. 4—CURVES SHOWING TIME REQUIRED AND VALUES DURING THIS TIME FOR AN UNSATURATED CADMIUM CELL TO RECUPERATE AFTER IT WAS SHORT-CIRCUITED FOR 30 MIN.

Curve No. 1 voltage vs hr. 1st day
Curve No. 2 voltage vs days up to 19 days
Total time to recuperate 36 days
Value before short circuit 1.019875 volts
Value after recuperation 1.019800 volts

Difference 0.000075 volts
Aug. 19, 1920

A cell short-circuited for one-half hour took eleven hours to recover to within 0.07 per cent of its former value, and 36 days to come back to within 0.007 per cent of its previous value. (Fig. 4.)

Three cells were short-circuited for ten minutes. At the end of seven hours they had recovered to within 0.02 per cent of their original values. A short-circuited cell should be regarded with suspicion, however, as the original equilibrium has been upset permanently because of the addition of cadmium to the electrolyte, if for no other cause.

In another experiment, three unsaturated cells (Weston type) with an internal diameter of 25 mm. were each connected across a resistance of such value as to cause 5 microamperes, 50 microamperes and 100 microamperes to flow in each cell respectively. The internal resistance of these cells was approximately 80 ohms. The initial e. m. f., the closed circuit e. m. f. after 6 minutes of current flow and the open circuit e. m. f. immediately after opening the circuit are given below.

	Microamperes		
	5	50	100
E. m. f. before closing circuit	1.01890	1.01886	1.01884
E. m. f. circuit closed 6 min.	1.01851	1.01481	1.01073
E. m. f. immediately on opening	1.01890	1.01882	1.01880

The same thing was done with three cells of 13.5 mm. internal diameter. The internal resistance of these cells was approximately 350 ohms. The results were as follows:

	Microamperes		
	5	50	100
E. m. f. before closing circuit	1.01890	1.01882	1.01884
E. m. f. circuit closed 6 min.	1.01698	1.00386	0.98994
E. m. f. immediately on opening	1.01883	1.01877	1.01874

The above indicates that not more than 0.7 microamperes per square millimeter of cross-section (in these cells, electrode area) can be taken for 6 minutes from a cell if a precision of 0.01 per cent is to be obtained.

It often has been stated that "not more than 0.0001 ampere should be taken from a cell." The results of the above experiment emphasize that as a matter of safety in measuring against a standard cell the closing key should be only just tapped and lengthy closing of the potentiometer circuit avoided.

Cells should not be exposed to the radiation from an electric light bulb. A 25-watt bulb 15 inches away and to one side of unmounted cells caused an increase in e. m. f. when the mercurous sulfate (positive) limb was exposed and the amalgam limb covered. The opposite arrangement caused a lowering of the e. m. f. Such exposure for five minutes brought about differences from the equilibrium value of the e. m. f. of from 100 to 200 microvolts (0.01 to 0.02 per cent). Even mounted cells have been known to show divergences of these magnitudes, or greater, when unequally exposed to the heating effects of lamps or to the disturbing effects of draughts of hot or cold air. The same can be said of heating by the hand in carrying from set-up to set-up.

Ten cells were packed in "dry ice." Two were proved to have been frozen solid. All recovered to within 0.1 per cent of their former values. This test is not conclusive but indicates that for precision work cells should not be frozen. This involves no hardship since the cryohydric point of cadmium sulfate is about −16 deg. cent.

It is surprising how many attempts are made to determine the e. m. f. of a standard cell by connecting it directly to a voltmeter. This method not only gives very poor accuracy, for reasons it is not necessary to go into, but injures the cell, for reasons of this same class.

From the foregoing discussion it would seem logical to conclude that the system of the cadmium standard cell is a sensitive one. This is no doubt true. It might also be concluded that the system cannot be set up so as to be stable. This is very far from true. Over fifteen years work upon the cadmium cell have given the writer ever-increasing confidence in its reliability. It is by no means foolproof, but then very few precision devices are foolproof. Ceaseless care must be given to its manufacture, and a thorough knowledge gained of its chemistry to insure the maximum of constancy and agreement. But there are few electrical measurements —if any, indeed—where so high a precision can be obtained with so little trouble as in comparisons of electromotive force based directly upon the standard cell.

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Discussion

For discussion of this paper see page 1324.

Design of Potentiometers

BY I. MELVILLE STEIN*

Member, A. I. E. E.

Synopsis.—This paper discusses potentiometer design under the following headings:

I. Early history. II. Factors affecting voltage range. III. Factors affecting potentiometer resistance. IV. Low-voltage potentiometers. V. Analysis of potentiometer errors. VI. Self-checking features of potentiometers. VII. Galvanometer considerations. VIII. Comments on volt-boxes. IX. Deflection potentiometers. X. The potentiometer in industry.

No attempt has been made to give the complete history of potentiometer development, as the paper is not intended to be primarily historical.

Neither has any attempt been made to include all of the circuits which have been used in high-resistance potentiometers and in the earlier forms of low-resistance potentiometers, as this would require too much time and space. Material of this kind has been limited to the minimum amount necessary to establish the proper background for the discussion of the subject.

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INTRODUCTION

THE paper is limited to the discussion of d-c., laboratory type potentiometers. It would be difficult to include a discussion of a-c. potentiometers without taking up numerous specific applications, because the a-c. potentiometer is to a large extent a special purpose instrument. The principal difference between the laboratory type of d-c. potentiometers included in this discussion and the industrial plant types of potentiometer is in the modifications necessary for the adaptation to particular applications. A general discussion of specific applications of the potentiometer in industry is beyond the scope of this paper and those interested in that subject are referred to a recent paper[1] in the *Journal of the Franklin Institute.*

I. EARLY HISTORY

A significant point in the early history of the potentiometer is that the circuit was developed for comparing the electromotive forces produced in primary cells; and then as now it was desired to measure the true e. m. f. of each cell, that is, the open circuit voltage. To accomplish this purpose, Johann Christian Poggendorf, a German philosopher, about the middle of the nineteenth century devised a "compensation" method which is shown in Fig. 1 and in which we have the relation

$$e = E\frac{r}{R+r}$$

where e is the open circuit voltage of cell X and E is the closed circuit voltage of cell S. Poggendorf's circuit was modified by the Frenchman DuBois Reymond[2] and further modified by Latimer Clark[3] in England about 1874 to give the general form of circuit now used in many potentiometers. (Fig. 2.) Here

$$e_2 = e_1\frac{r_2}{r_1}$$

where e_1 and e_2 are the open-circuit voltages of S and X, respectively, and r_1 and r_2 are the values of r to produce a balance with e_1 and e_2, respectively.

II. FACTORS AFFECTING VOLTAGE RANGE

In all of the early work, the open-circuit voltage of a primary cell was involved. Today, in all precise potentiometers, the open-circuit voltage of a primary cell is used for standardizing the potentiometer. This is the primary reason why most of the precise potentiometers have a range from zero to about 1.5 volts. There are, however, important exceptions to this.

In general, if the e. m. f. of the cell used for standardizing the potentiometer is approximately the same as the e. m. f. or potential difference to be measured, the measurement approaches a purely substitution method and the errors in the potentiometer itself become negligible. For instance, if in some research problem, requiring the utmost accuracy of measurement, it were desired to measure the relation between current and some other condition; then if the resistance of the current shunt were chosen to give, for the desired current, a potential drop of about 1.018 volt (the approximate value of a Weston standard cell), any error in the potentiometer itself could cause no measurable error in the determination of the current value.

Some potentiometers are designed so that ten times the normal current may be used, in which case the standardizing of the potentiometer current may be done with a series of ten standard cells. In this way, a range up to 10 or 15 volts may be provided without placing any greater dependence on the accuracy of the potentiometer resistances than is done in the potentiometers having a range up to about 1.5 volt. If such a potentiometer has also a low range, having one-tenth the value of the high range, then using ten times the normal current and only one standard cell, the current may be standardized on the low range, which thus becomes the 1.5-volt range and the nominal 1.5-volt range becomes a 15-volt range. However, if the standardizing is done in this way, the accuracy of the final measurement involves the accuracy of the range changing coils.

Potentiometer range changing devices are discussed

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*Director of Research, Leeds & Northrup Co., Philadelphia, Pa.

1. For references see end of paper.

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in a paper by Behr[4], and a recent potentiometer of the type shown in Fig. 2, but having three ranges is shown in Fig. 3.

The use of ten standard cells provides a somewhat more reliable reference e. m. f. than is available with a single standard cell. Practically the range cannot be increased indefinitely in this way because of difficulties due to leakage which would arise if a much higher voltage were applied directly to the potentiometer and for higher voltages a "volt box" is necessary.

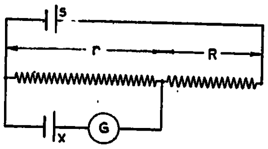

FIG. 1—POGGENDORF CIRCUIT

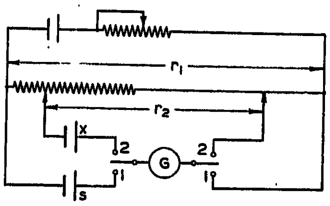

FIG. 2—MODIFIED LATIMER CLARK CIRCUIT

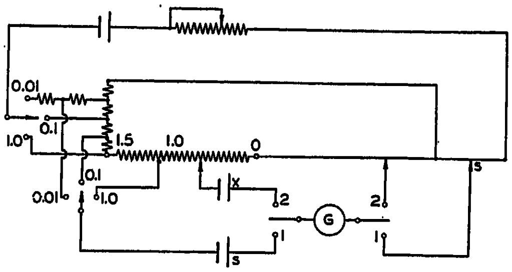

FIG. 3—MODERN THREE-RANGE POTENTIOMETER WITH SEPARATE STANDARD CELL DIAL (s)

For low-range potentiometers, having a maximum range of the order of 0.1 or 0.01 volt, full dependence must be placed on the accuracy of the potentiometer resistances as no standard of voltage is available which will permit making a direct substitution measurement. Such low-range potentiometers are essential for the precise measurement of temperature with thermocouples.

III. FACTORS AFFECTING POTENTIOMETER RESISTANCE

The total resistance of the potentiometer circuit is an important consideration in the design. Basically, the potentiometer is a voltage-measuring instrument, but the galvanometer, which is recognized as the most satisfactory device for indicating when the potentiometer is balanced or unbalanced, is basically a current detecting device. For any particular voltage unbalance in the potentiometer, the resulting galvanometer deflection varies with the current in the galvanometer circuit and this of course varies inversely with the total resistance in the galvanometer circuit. Accordingly, a higher resistance in the potentiometer reduces the sensitivity. This is true even though the galvanometer characteristics are correctly chosen for the high-resistance circuit. This point is discussed more fully below.

For the same voltage range, the current through the potentiometer resistances varies inversely with the potentiometer resistance; for example, if a 1.5-volt range potentiometer has a resistance of 75 ohms, the current will be 0.02 ampere and if the potentiometer resistance is 15,000 ohms, the current will be 0.0001 ampere. As the impressed voltage is the same in either case, the leakage current around the potentiometer resistances will be the same, but a leakage current of a particular value will cause 200 times the error in the 15,000-ohm potentiometer that it will in the 75-ohm potentiometer. This is a serious disadvantage in working with the very small potentiometer current which results if a very high resistance is used in the potentiometer circuit.

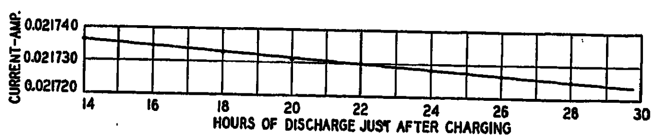

FIG. 4—CURRENT CHANGE IN LEAD STORAGE CELL 60-AMPERE-HOUR CELL DISCHARGING THROUGH 100 OHMS

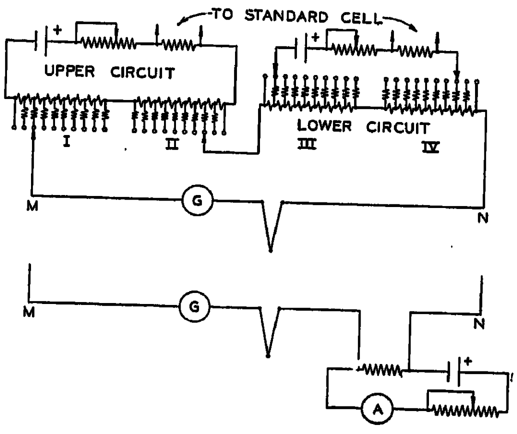

FIG. 5—(UPPER) WHITE POTENTIOMETER CIRCUIT (LOWER) ADDITION OF LINDECK AND ROTHE CIRCUIT

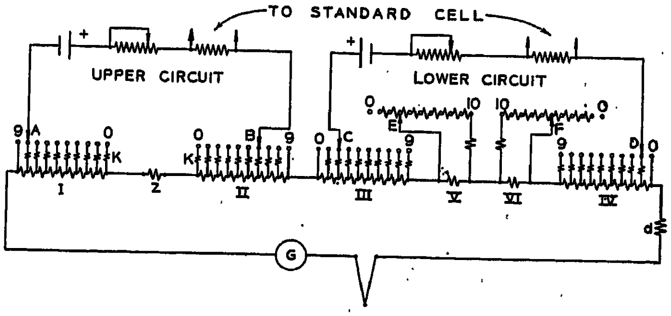

FIG. 6—TWO-RANGE 5-DIAL LOW RESISTANCE POTENTIOMETER

An advantage sometimes claimed for the smaller potentiometer current, but which is more apparent than real, is the smaller drain on the working battery. In this connection, it should be remembered that storage batteries having capacities upwards of 50 ampere-hours are now readily available at very low cost and the effect of a drain of 0.02 ampere on such a battery is very small. (Fig. 4.) Unless the battery is lagged or thermostated, temperature changes are likely to be of more importance than current drain in causing unsteadiness of the potentiometer current and the temperature effect is the same for a drain of either 0.0001 ampere or 0.02 ampere on a battery of 50 ampere-hour capacity. The temperature coefficient of the voltage[5] of a lead storage cell is 0.0004 volt per deg. cent. Probably the objection to using a current of 0.01 or 0.02 ampere in the potentiometer had its origin in the days prior to the advent of the low-price, high-capacity storage-cell and prior to the invention of M. E. Leeds and E. F. Northrup[6] which made it possible to check the potentiometer current instantly without changing the potentiometer setting.

Another important design consideration which involves the potentiometer resistance is the comparative stability of low-resistance and high-resistance coils. While it is extremely difficult to design and construct unsealed resistance coils of 1,000 ohms which will remain constant to 0.01 per cent over long periods of time, it is comparatively easy to construct coils of 1 to 10 ohms resistance which will have this degree of constancy. This is another reason for avoiding a high resistance in the main circuit of the potentiometer.

An additional difficulty arising from the use of a high-resistance potentiometer circuit is involved in the proper damping of the galvanometer. This is discussed more in detail below, and here it is sufficient merely to point out that the resistance introduced into the galvanometer circuit by an ordinary potentiometer varies considerably as the potentiometer setting is changed and if the potentiometer resistance is high, extra compensating resistance adjustments are necessary to keep the galvanometer properly damped.

With a low-resistance potentiometer circuit, it is often possible to simplify the construction greatly by using a slide wire to cover as much as one-tenth of the voltage range. This is impractical with a high-resistance circuit because of the small diameter of slide wire required. The slide wire is not at all essential to the construction of a low-resistance potentiometer and some low-resistance potentiometers are constructed with dial decades throughout. Potentiometers of this latter design are discussed in detail below.

IV. Low-Voltage Potentiometers

For making precise temperature measurements with thermocouples, accurate low-range potentiometers are required. A copper constantan thermocouple produces a voltage of only about 40 microvolts per deg. cent. and a precision of 0.001 deg. cent. is not an uncommon requirement. This would mean a precision of 0.04 microvolt if only one thermocouple were used, and it is sometimes desirable or necessary to use only a single thermocouple. A practical case would include the following considerations. The "cold junction" or reference junction of the thermocouple would be maintained at 0 deg. cent. because of the accuracy with which the icepoint can be determined and the "hot junction" or measuring junction probably would be at about 30 deg. cent. in a constant temperature bath. Better control can be obtained if the bath temperature is a little above room temperature. If a precision of a few thousandths of a deg. cent. were required, say 0.003 deg. cent., this would mean a precision of 0.01 per cent and 0.12 microvolt. It will be seen at once that a total parasitic e. m. f. of a few microvolts anywhere in the circuit would prevent obtaining the desired precision.

Referring now to the potentiometer circuit, parasitic e. m. fs. are introduced by sliding contacts whether of the dial switch or slide wire type. A fair value to assign to these parasitic e. m. fs. is 1 microvolt per switch contact and 2 or 3 microvolts for a well designed slide-wire contact. Dial switches frequently are designed with 2 contacts per switch so that the possible parasitic e. m. f. would be 2 microvolts per switch. Accordingly, ordinary switch or slide-wire contacts that must be moved frequently cannot be tolerated in the thermocouple circuit; and the galvanometer, which also must be in the thermocouple circuit, must be of such design as to introduce no appreciable parasitic e. m. f.

The arrangement which is generally used in the design of potentiometers for this class of service is to transfer those sliding contacts which must be moved frequently, to the potentiometer battery circuit or to some other circuit in which the contact e. m. f. does not combine directly with the measured e. m. f. (See Fig. 6.) For such service, the potentiometer resistance must be low (not much in excess of 100 ohms) because of the sensitivity required. In a low-resistance circuit even the high-grade slide wire contacts which serve admirably in the galvanometer circuit of a potentiometer of the ordinary range have too much variation in resistance (0.01 to 1.0 ohm) to permit their use in a circuit which must remain constant in resistance while the potentiometer adjustments are being made.

It must not be assumed that by avoiding sliding contacts directly in the thermocouple circuit, the problem is entirely solved. Parasitic e. m. f. must be avoided in the galvanometer itself (see below), but even then, there may remain a small and comparatively constant parasitic e. m. f. which must be taken into account in work of extreme precision by using a false zero-setting of the galvanometer.

The best null potentiometer for this work, therefore, would appear to be a low-resistance instrument with dial decades for all settings. A further refinement is to keep the galvanometer circuit resistance constant for all potentiometer settings. This permits interpreting deflections of the galvanometer to give readings in between steps of the lowest dial and increases the speed of operation because good galvanometer damping is maintained. It also avoids disturbing the "false zero" of the galvanometer if this expedient is used.

Probably the simplest, complete potentiometer circuit of this general form is that devised by Walter P. White[7] and shown in Fig. 5. Here it will be seen that the sliding contacts of the two dials which are used for measuring temperature changes are in the battery circuit. The contacts of the two dials which are moved only very infrequently are shown in the thermocouple circuit. They could be placed in the battery circuit very readily, but there is little to choose between the two arrangements because constancy of battery circuit resistance in the two higher voltage dials is just as important as absence of parasitic e. m. f., the important consideration being that these switches are seldom, if ever, moved, once the initial setting is made.

It will be noted that the White circuit permits the use of four dials, values lying between steps on the fourth dial being determined from the deflection of the galvanometer which operates in a constant resistance circuit. The arrangement is really that of two 2-dial potentiometers with the thermocouple circuits connected in series. Two separate balances must be made against the standard cell, one for each potentiometer, but this is not a serious disadvantage because when the first or second dial is in circuit, the accuracy of the current adjustment through the third and fourth dials need not be high; accordingly, the current in this circuit needs adjustment only very infrequently.

The White potentiometer is ordinarily made with a single range, either 10,000 or 100,000 microvolts. The galvanometer circuit resistances are 40 ohms and 300 ohms, respectively. Instruments of both ranges may be equipped with a second set of dials to provide a double potentiometer. In the double potentiometer, two values of potential differing widely from each other may be measured without disturbing the dial settings. This arrangement is an adaptation of the independent standard cell balancing dial[6] previously mentioned.

The equivalent of an additional dial on the White potentiometer may be provided by connecting the device of Lindeck and Rothe[8] in the thermocouple circuit. (See Fig. 5.)

A two-circuit potentiometer suggested by the author for this class of work is shown in Fig. 6. Here the two thermocouple circuits, instead of being connected to give the sum of the two potentials, are connected to give the difference of the two potentials. This arrangement avoids the requirement of reducing both potentials to zero to obtain a zero reading on the potentiometer and therefore makes possible the inclusion of one or two shunted decades[9] to give 5 or 6 dials instead of the 4 dials provided in the White potentiometer. Only 5 dials would be used at one time, the extra dial being a convenient means for making the range of the potentiometer either 10,000 microvolts or 100,000 microvolts.* It will be apparent that numerous variations of this general arrangement are possible. The potentiometer of Fig. 6 has a practically constant resistance of about 11 ohms in the galvanometer circuit. This general circuit requires two batteries for supplying the potentiometer and, consequently, two adjustments against the standard cell just as in the White potentiometer.

Low-voltage potentiometers have been devised which utilize the same "difference" principle as is used in the potentiometer of Fig. 6, but which use only one battery and require only one balance against the standard cell. These are commonly called "split-circuit" potentiometers and are shown in Fig. 7 and Fig. 8. The potentiometer of Fig. 7 was proposed by Diesselhorst[10] and involves some elements proposed by Hausrath, White, Waidner and Wolff.[11] The one shown in Fig. 8 uses a development of the circuit suggested by Wenner.[12] The former has a normal range of 10,000 microvolts and a practically constant resistance in the galvanometer circuit of about 14 ohms. The latter has two ranges of 100,000 and 10,000 microvolts and has a practically constant resistance in the galvanometer circuit also of about 14 ohms.

There are at present no published papers giving a complete description of the modified Wenner potentiometer of Fig. 8, but such a paper is in preparation and will shortly be published.

V. Analysis of Potentiometer Errors

Reference has been made to the stability of high-resistance and low-resistance coils and to resistance variation and parasitic e. m. f. at switch and slide wire contacts. The following analysis should help to make clear the significance of these factors.

Reference to Fig. 2 will show that when both potential contacts are set on zero, they are connected to the identical point in the current circuit. Accordingly, there can be no potential difference between them no matter what may be the value of the potentiometer current. In other words, the potentiometer has a true zero point. This arrangement makes possible a simple low-resistance potentiometer and, as indicated above, low resistance in the potentiometer is much to be desired.

Fig. 9 shows the well-known potentiometer circuit due to Feussner.[13] This potentiometer is usually made with a very high total resistance of (20,000 ohms). This high resistance is not desirable, but is necessary because of the large number of contacts in the circuit. It is important to note that the error in microvolts, due to residual resistance in a circuit of this kind, is a constant one and not a proportional one; in other words, it produces a false zero. The error is equal to the residual resistance multiplied by the potentiometer current. In the Feussner design, a very high resistance is used to keep the potentiometer current small (0.0001 ampere) so that the error due to the residual resistance is usually negligible in the class of potentiometers in which the true Feussner circuit is used. If a potentiometer were made using a circuit similar to the Feussner circuit, but which required a potentiometer current of 0.01 ampere, it would be evident that the constant error due to residual resistance in such a potentiometer would be 100 times as large as the error in the Feussner instrument for the same residual resistance.

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*The use of all six dials at one time, to measure absolute voltage values, would imply a higher accuracy in the main potentiometer coils and in the value of the standard cell than is justifiable. All six dials may be used at one time for measuring small changes in voltage such as might be encountered in calorimeter measurements in which the temperature changes are observed by means of thermocouples.

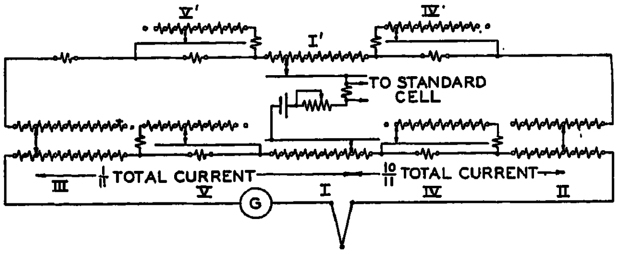

Fig. 7—Diesselhorst Potentiometer Circuit

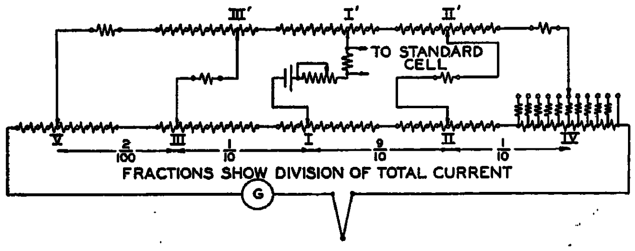

Fig. 8—Wenner Potentiometer Circuit

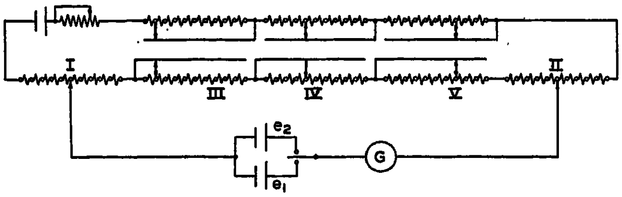

Fig. 9—Feussner Potentiometer Circuit

Referring now to the potentiometer circuit shown in Fig. 6, the contacts A, B, C and D are all in the battery circuits where the voltage is about 2 volts and the resistance in the upper battery circuit is 200 ohms and in the lower battery circuit 2,000 ohms. In view of the comparatively high voltage of the battery circuit, the error due to parasitic e. m. f. at the contacts is, of course, negligible. The microvolt error, due to variation of resistance at the contacts, is proportional, not constant, and will never cause an error in per cent greater than $\frac{\Delta r}{R} \times 100$, where Δr is the variation in contact resistance and R is the battery circuit resistance. Assuming 0.0002-ohm variation in resistance, for a 200-ohm battery circuit, this would be 0.0001 per cent, and for a 2,000-ohm battery circuit, this would be 0.00001 per cent.

Contacts E and F in Fig. 6 produce negligible errors from either variation in contact resistance or parasitic e. m. f. The circuit in which these contacts are placed is such as to make the effective variation due to resistance entirely negligible and to make the effective parasitic e. m. f. less than 1 per cent of the actual contact e. m. f. (See Appendix I.) The manipulation of contacts E and F causes a negligible variation in the current in the lower potentiometer circuit. If an arrangement of this kind were used in the upper potentiometer circuit where the total resistance is lower, compensating coils would be necessary to correct for the variation in potentiometer current.

The additional errors which need consideration in the potentiometer proper are the errors in the resistance coils. These fall into three groups: (1) the main potentiometer coils; (2) the compensating coils, and (3) the coils bridged by the standard cell in standardizing the potentiometer current. Frequently, coils are placed in circuit in such a way that they belong in more than one of these groups. Here it is desired merely to say that if coils not much above 100 ohms are used, there is no great difficulty in making them and adjusting them so that the error will not exceed 0.01 per cent over long periods.

A summation of errors due to the above causes for the 100,000 and 10,000 microvolt ranges of the potentiometer, shown in Fig. 6, is given in Appendix II. These are maximum errors, the probable errors being somewhat less. It will be seen that for both ranges, the maximum error is less than the value of one step on the last dial.

VI. Self-Checking Features of Potentiometers

The measurements for which potentiometers are used are usually those on which great dependence is to be placed and, accordingly, the user should never be in doubt about the accuracy of his potentiometer. Even with the best design, workmanship and materials, a potentiometer may be made inaccurate by abuse or use by a careless operator, and, to guard against errors from such causes, the potentiometer design, if possible, should be such as to permit convenient checking by the user. Fortunately, the nature of the ordinary potentiometer circuit is such as to permit checking to a high degree of accuracy with instruments which are of a much lower order of accuracy. However, to facilitate the work of checking, the potentiometer circuit should be kept as simple as possible.

Usually, there are provided low-resistance plug blocks, all alike, for making connections to each of the main potentiometer coils so that their values may be compared for equality using a wheatstone bridge. Since it is necessary to measure only the difference between values which in a good instrument are alike within 0.01 per cent, errors as large as 10 per cent in the bridge used for checking would cause an inaccuracy of only 0.001 per cent in the result. After the equality of the main resistors has been determined in this way, the calibration of the slide wire is checked against the main resistors; see Fig. 10. If the comparative values of the main resistors are known to 0.01 per cent, the uniformity of the slide wire may be determined with this same precision.

The final step is to determine the ratio between the main potentiometer resistors and the resistance across which the standard cell is connected when standardizing the potentiometer current. By making the standard cell balance across the identical resistors that comprise the main potentiometer resistance, it is obvious that the ratio must be exactly unity. For convenience, it is desirable to make a small part of the resistance, across which the standard cell is balanced, a separate adjustable unit. This small adjustable resistance may be checked against the main slide wire as shown in Fig. 11. With the main slide wire on zero and the standard cell dial at its maximum setting the battery current is adjusted to produce a balance against the standard cell. The standard cell dial is then changed in steps and the resistance change for each step is found by adjusting to a balance with the main slide wire.

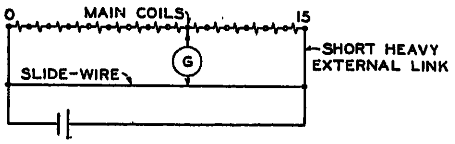

Fig. 10—Checking Potentiometer Slide-Wire Against Main Coils

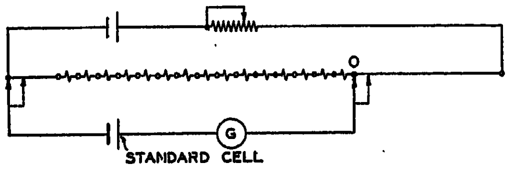

Fig. 11—Checking Standard Cell Adjustment Against Main Slide Wire

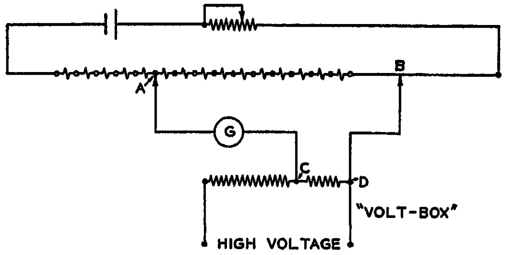

Fig. 12—"Volt-Box" Connections

VII. Galvanometer Considerations

The improvement in sensitivity resulting from low resistance in the potentiometer circuit has been previously mentioned. A common example will be found in the measurement of current in the standardizing laboratory. Here, if a comparison is made on the basis of using galvanometers of the same general type and period, it is found that generally the energy consumption in the current shunts is much less when working with a low-resistance potentiometer. The lower energy consumption reduces the cost of the shunts and avoids the inconvenience of providing oil and water cooling. If the comparison is made on the basis of equal energy consumption in the current shunts, then the low-resistance potentiometer has the advantage that a more sturdy and convenient and less expensive galvanometer can be used. For instance, if a 300-ampere current shunt is made with a resistance of 0.001 ohm, it will produce a voltage drop of 0.3-volt at full load. A precision of measurement of 0.01 per cent would require a sensitivity of 30 microvolts. With a potentiometer having a total resistance of 100 ohms, the galvanometer circuit resistance due to the potentiometer for a setting of 0.3-volt is 12.75 ohms. With a potentiometer having a total resistance of 20,000 ohms, the corresponding resistance is 2,550 ohms. A convenient galvanometer suitable for use in the low-resistance circuit would have a resistance of 20 ohms, a current sensitivity of 0.25 microampere per millimeter, a voltage sensitivity of 25 microvolts per millimeter with an external critical damping resistance of 80 ohms and a period of 3 seconds. The difference between 12.75 ohms and 80 ohms would be made up with a resistance coil of about 67 ohms. Reading to the nearest millimeter would give the desired precision.

If this same galvanometer were used with the high-resistance potentiometer, the voltage sensitivity with 2,550 ohms in circuit would be 643 microvolts per millimeter. This would require reading to about 0.05 millimeter, which is impractical, and, in addition, the galvanometer would be badly underdamped. If proper damping is taken into consideration, the required sensitivity of 30 microvolts is impossible to obtain with the design of galvanometer under consideration. Accordingly, it is necessary to use a more sensitive and more costly form of galvanometer or materially to increase the resistance of the current shunt with a consequent increase in energy loss and cost.

Proper damping of the galvanometer is essential to rapid working with the potentiometer and the damping of modern galvanometers, designed to have short periods and high sensitivities, is much more affected by the external circuit resistance than were the older galvanometers having long periods and much lower sensitivities. Consequently, it is very desirable that the circuit resistance external to the galvanometer should be approximately constant. In a 20,000-ohm potentiometer, the probable resistance variation in the galvanometer circuit, as the dials are manipulated, is in excess of 4,000 ohms, while in a 100-ohm potentiometer, the corresponding resistance variation is approximately

20 ohms. Accordingly, when working with a very high-resistance potentiometer, it is impossible to keep the galvanometer properly damped unless some auxiliary compensating resistance is adjusted each time a substantial change is made in the potentiometer setting. (See Appendix III for calculations.)

When working with low-range potentiometers, such as those shown in Figs. 5 to 8, it is not sufficient merely to avoid parasitic e. m. fs. in the potentiometer proper because the galvanometer itself may be the seat of a parasitic e. m. f. amounting to 5 or 10 microvolts under ordinary working conditions. By making the entire galvanometer circuit of copper, the parasitic e. m. f. is reduced to a small fraction of a microvolt.[14]

VIII. Comments on Volt-Boxes

Usually, for extending the potentiometer range above 1 or 2 volts, a voltage divider known as a "volt-box" is used. The connections are shown in Fig. 12. It is desirable to make the total resistance of a volt-box reasonably high, several hundred ohms per volt, first, to avoid lead and contact errors in the high-voltage circuit, and, second, to reduce the energy dissipation in the coils. A much higher resistance is undesirable because the higher resistance coils are likely to be less stable and because the higher resistance in the galvanometer circuit reduces the sensitivity. Some publications[15,16] state that a low-resistance volt-box should be used with a low-resistance potentiometer and that a high-resistance volt-box should be used with a high-resistance potentiometer. This is incorrect. In considering lead and contact errors or energy dissipation in the coils, the potentiometer resistance is not involved. The consideration of sensitivity does involve the potentiometer resistance, but if the maximum resistance introduced into the galvanometer circuit *A-B* (Fig. 12) by a low-resistance potentiometer is 25 ohms and by a high-resistance potentiometer is 5,000 ohms, it is obvious that the galvanometer circuit resistance *C-D* in the volt-box may be 4,975 ohms higher with the low-resistance potentiometer to give the same sensitivity.

IX. Deflection Potentiometers

In the deflection potentiometer, the principal part of the potential being measured is balanced against a known potential just as is done in an ordinary null potentiometer and the remaining small portion of the unknown potential is read from the deflection of a calibrated galvanometer. While the general idea was suggested by Stansfield[17] as early as 1898 and was used by Hoffman and Rothe[18] in 1905, the complete development of the idea as applied to precise laboratory potentiometers is due to H. B. Brooks of the Bureau of Standards. The principles underlying the design of deflection potentiometers have been so well presented in the publications[19] of the Bureau of Standards that they need not be discussed here. It will suffice to say that the fundamental requirement in the design of a deflection potentiometer is that for all connections and adjustments of the potentiometer, there must be no appreciable change in the galvanometer circuit resistance.

Instead of going into the design of the deflection potentiometer, it is desired to state the advantages of the instrument in one important class of measurements. Aside from its use in photometric measurements, the most important application of the deflection potentiometer is in checking large numbers of portable indicating instruments. Discussing this latter problem, Brooks, in his original publication[19] on the deflection potentiometer points out that null potentiometers are the most accurate for the purpose, but require too much time to use and that long scale "laboratory standard" deflecting instruments, while faster in operation, are not sufficiently accurate for the purpose. He concludes that "the need unquestionably exists for a type of instrument for current and voltage measurements which will have properties intermediate between those of the ordinary deflection instrument and the elaborate potentiometer."

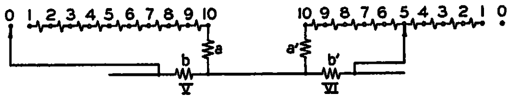

Fig. 13—Dials V and VI of Fig. 6

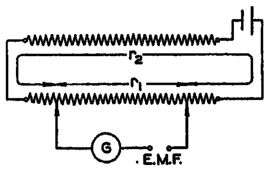

Fig. 14—Potentiometer Resistance in Galvanometer Circuit

It is interesting to note that although the deflection potentiometer does provide an instrument intermediate in accuracy between the null potentiometer and the laboratory standard deflection instruments, it is not intermediate in speed of operation. It is faster than either of the other two types of instrument. There are several reasons why the deflection potentiometer is more rapid in operation than the laboratory standard deflection instrument. In the deflection potentiometer, the deflecting pointer is shorter and lighter and this results in a shorter period; it is unnecessary to take the time to estimate tenths of a division because reading to the nearest division is all that is required and finally, because in the deflection potentiometer, the position of the pointer does not change very much and need not be observed more closely than one division, it is unnecessary for the operator to change his position frequently in order to remain in line with the pointer. This latter precaution is essential in reading laboratory standard deflection instruments to avoid parallax errors.

X. THE POTENTIOMETER IN INDUSTRY

Mention has been previously made of the use of the potentiometer in industrial plants. It may be of interest to point out that in recent years the use of potentiometers in industrial plants has increased to such an extent that a fair estimate indicates that nine-tenths of potentiometers put into use each year go into industrial plant applications and only one-tenth go into laboratory service. This is not due to any falling off in the laboratory uses of potentiometers. The potentiometer is more generally used in laboratories than ever. It is due entirely to the very rapid increase in industrial plant uses of the instrument, in the form of portable indicating potentiometers and automatic recording and controlling potentiometers.

ACKNOWLEDGMENT

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Appendix I

CALCULATION OF ERRORS IN WAIDNER-WOLFF SHUNT-DECADE

In the circuit where these shunted decades are used (see Fig. 6), the e. m. f. opposes the principal e. m. f. in the potentiometer circuit. Accordingly, a decrease in the e. m. f. in this circuit will cause a net increase in the potentiometer e. m. f. Therefore, with a constant current, the effective resistance should decrease for increasing dial readings. This decrease of resistance is obtained by shunting the coils b and b', the shunting resistance decreasing in value as the dial readings increase. The coil values are given in the following table:

TABLE I—COIL VALUES (OHMS) DIALS V AND VI OF FIG. 6

	Dial V Shunted coil (b) $= \sqrt{1.26} = 1.1225$ ohm		Dial VI Shunted coil (b') $= \sqrt{0.126} = 0.3550$ ohm	
Dial position	Total shunting resistance (R_s)	Individual coil resistance	Total shunting resistance (R_s)	Individual coil resistance
10.....	$126.0 - \sqrt{1.26}$	$124.8775 - a$	$126.0 = \sqrt{0.126}$	$125.645 = a'$
9.....	140.0 − "	14.0	140.0 − "	14.0
8.....	157.5 − "	17.5	etc.	17.5
7.....	180.0 − "	22.5		22.5
6.....	210.0 − "	30.0		30.0
5.....	252.0 − "	42.0		42.0
4.....	315.0 − "	63.0		63.0
3.....	420.0 − "	105.0		105.0
2.....	630.0 − "	210.0		210.0
1.....	1260.0 − "	630.0		630.0
0......	Infinity.....	Infinity...		...Infinity

NOTE: A similar selection of coil values for shunt-decades was described by E. F. Mueller,[20] who derived values for the shunted resistance b and b' to make most of the individual coil resistances simple values and identical in both decades.

In addition to errors in the resistance coils, the possible sources of error in such shunt-decades are the resistance and the parasitic e. m. f. at the contact. Most of the resistance coils are low in value so that, with good construction, the error due to lack of stability is negligible. Lack of stability in any of the few higher resistance coils needs to be considered.

The error due to contact resistance will be equal to the error introduced in the joint resistance of the shunted and shunting coils, and will have its maximum value when the shunting resistance has its minimum value. The joint resistance is

$$R_j = \frac{r\,(R_s + \Delta R)}{r + R_s + \Delta R}$$

where

R_j = joint resistance of shunted and shunting coils
r = shunted resistance (b or b')
R_s = shunting resistance (minimum value a or a')
ΔR = variation in contact resistance

The error in R_j due to contact resistance ΔR, expressed in per cent is:

$$\text{per cent error} = \frac{r \,.\, \Delta R}{R_s\,(R_s + \Delta R + r)} \times 100$$

Taking approximate values for the coils of dial V and assuming a contact resistance of 0.0002 ohm, this gives,

$$\text{per cent error} = \frac{0.02}{125\,(125 + 0.0002 + 1)} = 0.00000125$$

Expressed another way and for the particular resistance values used, the change in the joint resistance R_j for a contact resistance ΔR is less than $0.0001\,\Delta R$.

The joint resistance in dial V is approximately 1 ohm and changes precisely 0.001 ohm for each step of the dial. The joint resistance in dial VI is approximately one-third of an ohm and changes precisely 0.0001 ohm for each step of the dial.

The error due to contact e. m. f. will be the e. m. f. produced in the galvanometer circuit by the contact when all other potentials in the circuit are assumed to be zero. Any effect in or because of the battery circuit is too small to be considered. The following notation is used:

$e = i\,r$ = e. m. f. produced in galvanometer circuit by contact e. m. f.
r = resistance of shunted coil (b or b')
i = current produced in r by contact e. m. f.
ϵ = contact e. m. f.
I = total current produced by ϵ
R_s = shunting resistance
R_g = resistance in galvanometer circuit exclusive of shunted resistance of r
R_j = joint resistance in series with ϵ

Then:

$$I = \frac{\epsilon}{R_j} = \frac{\epsilon}{R_s + \dfrac{r\,R_g}{r + R_g}}$$

$$= I \,.\, \frac{\dfrac{r\,R_g}{r + R_g}}{r}$$

$$= \epsilon \,.\, \frac{\dfrac{r\,R_g}{r + R_g}}{r\left(R_s + \dfrac{r\,R_g}{r + R_g}\right)}$$

$$e = i\,r = \epsilon \,.\, \frac{r\,R_g}{r\,(R_s + R_g) + R_s\,R_g}$$

Again taking approximate values for dial V, taking R_g as 40 ohms (Appendix 2) and assuming a contact e. m. f. of 1 microvolt, this gives

$$e = \frac{40}{125 + 40 + 5000} = 0.008 \text{ microvolt}$$

Expressed another way and for the particular coil values used

$$e = 0.008\,\epsilon$$

Referring now to stability of resistance coils, there are only two coils in the decade which are much above 100 ohms. These have values of 210 ohms and 630 ohms. There is no observable difference in stability between a coil of 210 ohms and one of about 100 ohms, both being able to retain their values well within 0.01 per cent. By reference to the above equation showing the minute error caused by a contact resistance, ΔR, of 0.0002 ohm, it will be seen that a contact resistance of 16 ohms would cause an error of only 0.1 per cent. An error in the 630-ohm coil of 16 ohms would cause a hundredth of this error because of the value of R_s when the 630-ohm coil is in circuit. An error of 16 ohms would correspond to a change of over 2 per cent in the value of the 630-ohm coil and any such large change in a 630-ohm coil which was not defective would be impossible.

Accordingly, the only errors in the shunt-decade which need be taken into account in a summation of errors are the error in the value of the shunted resistance r (b or b') and the error introduced by the contact e. m. f. ϵ. The value of r in dial V is approximately one ohm and therefore can be depended upon to better than 0.01 per cent. The error caused by the contact e. m. f. ϵ is less than 1 per cent of the value of ϵ. Similar calculations using the coil values for dial VI show a negligible error for variation in contact resistance and a value for e of 0.003 microvolt.

Appendix II

CALCULATION AND SUMMATION OF ERRORS LOW-RANGE, FIVE-DIAL POTENTIOMETER—FIG. 6

This instrument is referred to as a five-dial potentiometer although six dials are used. The reason for this is that only five dials are used at one time, the sixth providing a convenient means for changing the range. When dials I to V are used, the range is 100,000 microvolts and when dials II to VI are used, the range is 10,001 microvolts.

The current in the upper circuit is 0.01 ampere and in the lower circuit 0.001 ampere for either range. Using 2-volt batteries, the battery circuit resistance in the upper circuit is 200 ohms and in the lower circuit is 2,000 ohms. The actual galvanometer circuit resistance is approximately 11 ohms, but an auxiliary coil d is included to bring the resistance up to 40 ohms, which is the external critical damping resistance value of a good galvanometer of proper sensitivity and period.

The coil values for dials V and VI are given in Appendix I. The principal potentiometer coils for the remaining dials are given below.

Dial I......	nine 1.0-ohm coils
Dial II.....	nine 0.1-ohm coils
Dial III....	nine 0.1-ohm coils
Dial IV.....	nine 0.01-ohm coils

It will be seen at once that there are no sliding contacts directly in the galvanometer or thermocouple circuit. The contact e.m.f. produced in the galvanometer circuit by dials V and VI is given in Appendix I. The contacts of dials I, II, III and IV are in the battery circuits. As any parasitic e. m. f. at the contacts of these four dials is effective only in changing the battery currents, the author has found it convenient to convert these parasitic e. m. fs. into equivalent resistances. Assuming a maximum parasitic e. m. f. of 1 microvolt per contact, the equivalent resistance is 0.0001 ohm per contact in the 200-ohm, 2-volt battery circuit and 0.001 ohm in the 2,000-ohm, 2-volt battery circuit. Contact resistance changes in these four dials are assumed to be 0.0002 ohm per contact. The final assumption is that the compensating coils k are adjusted to cause no error greater than 0.01 per cent in dials I and II and no error greater than 0.1 per cent in dials III and IV.

It should be noted that any change in battery current in the upper circuit affects dials I and II and any change in battery current in the lower circuit affects dials III, IV, V and VI.

The coil z in the upper circuit is of such value as to produce a potential drop in that circuit just equal to the maximum drop in the lower circuit. This occurs when all dials of the lower circuit are set on zero and is 2467.5 microvolts. Dials I and II add 99,000 microvolts so that the maximum potential drop in the upper circuit is 101,467.5 microvolts.

For small resistance changes, the maximum per cent error in current in either circuit, due to operation of the dials, is the same as the maximum per cent variation in equivalent resistance and is obtained as follows:

$$\text{Variation in current} = \frac{\Delta R}{R} \cdot 100 \text{ per cent}$$

where R is the battery circuit resistance and ΔR is the maximum variation in equivalent resistance due to operation of all the dials in the circuit.

Computation of ΔR for Upper Circuit

Contact resistance change..........	2 × 0.0002 ohm	= 0.0004 ohm
Equivalent resistance change (contact e. m. f.).....................	2 × 0.0001 "	= 0.0002 "
Compensating coil error Dial I.....	9 × 0.0001	= 0.0009 "
Compensating coil error Dial II....	0.9 × 0.0001	= 0.00009 "
ΔR = maximum equivalent resistance variation.......		= 0.00159 ohm

Computation of ΔR for Lower Circuit

Contact resistance change..........	2 × 0.0002 ohm	= 0.0004 ohm
Equivalent resistance change (contact e. m. f.).....................	2 × 0.001 "	= 0.0020 "
Compensating coil error Dial III...	0.9 × 0.001	= 0.0009 "
Compensating coil error Dial IV...	0.09 × 0.001	= 0.00009 "
Resistance change due to Dial V....	10 × 0.001 ohm	= 0.0100 "
Resistance change due to Dial VI...	10 × 0.0001 "	= 0.0010 "
ΔR = maximum equivalent resistance variation.......		= 0.01439 ohm

Microvolt Error in Upper Circuit due to Resistance Changes

$R = 200$ ohms

$$\frac{\Delta R}{R} \cdot 100 = 0.5\,\Delta R \qquad = 0.0008 \text{ per cent}$$

Maximum microvolt error $= 101{,}467.5 \times 0.000008$
$= 0.81$ microvolt

Microvolt Error in Lower Circuit due to Resistance Changes

$R = 2{,}000$ ohms

$$\frac{\Delta R}{R} \cdot 100 = 0.05\,\Delta R \qquad = 0.00072 \text{ per cent}$$

Maximum microvolt error $= 2467.5 \times 0.0000072$
$= 0.018$ microvolt

SUMMATION OF ERRORS DUE TO DIAL OPERATION 100,000-MICROVOLT RANGE

Error due to resistance changes, upper circuit..........	0.807 microvolt
Error due to resistance changes, lower circuit...........	0.018 "
e. m. f. produced in galvanometer circuit by contact of dial V..	0.008* "
e. m. f. produced in galvanometer circuit by contact of dial VI.......................................	0.003* "
Total microvolt error........................	0.836 "

*See Appendix I.

This summation includes slight errors due to operation of dial VI, which, as stated before, would be used on the 100,000 microvolt range, only when observing small changes of voltage such as encountered in calorimetry.

To obtain the total error for the 10,000 microvolt range, the error due to dial I should be omitted, as dial I would be set on zero and would not be operated.

Microvolt Error in Upper Circuit—10,000 microvolt range

Contact resistance change................................	0.0002 ohm
Equivalent resistance change (contact e. m. f.)..........	0.0001 "
Compensating coil error Dial II 0.9 × 0.0001 =........	0.00009 "
ΔR = maximum equivalent resistance variation =......	0.00039 ohm

$R = 200$ ohms

$$\frac{\Delta R}{R} \cdot 100 = 0.5\,\Delta R = 0.0002 \text{ per cent}$$

Microvolt error $= 11{,}467.5 \times 0.000002$
$= 0.023$ microvolt

SUMMATION OF ERRORS DUE TO DIAL OPERATION 10,000-MICROVOLT RANGE

Errors due to resistance changes, upper circuit..........	0.023 microvolt
Errors due to resistance changes, lower circuit..........	0.018 "
e. m. f. produced in galvanometer circuit by Dial V.....	0.008* "
e. m. f. produced in galvanometer circuit by Dial VI....	0.003* "
Total microvolt error........................	0.052 "

*See Appendix I.

When using the 100,000-microvolt range, one step of the lowest dial (dial V) is 1 microvolt and when using the 10,000-microvolt range, one step of the lowest dial (dial VI) is 0.1 microvolt. Accordingly, the maximum error due to switch operations is less than one step on the low dial for either range and of course the probable error is even less.

It should be noted that these summations of errors do not include the usual errors due to the residual inaccuracy in the main potentiometer coils. An inaccuracy of 0.01 per cent in these coils would cause a maximum microvolt error equal to one step on the fourth dial in use for either range. Facilities must be available for determining the values of the main coils to 0.001 per cent if the main coil resistance error is not to exceed the error due to switch operations.

Appendix III

VARIATION IN GALVANOMETER CIRCUIT RESISTANCE OF POTENTIOMETERS

If,

R = total resistance in battery circuit of potentiometer

R_g = effective potentiometer resistance in galvanometer circuit

r_1 = potentiometer resistance directly in galvanometer circuit

r_2 = resistance shunting r_1

Then,

$$R = r_1 + r_2$$

$$R_g = \frac{r_1 r_2}{r_1 + r_2} = \frac{R r_1 - r_1^2}{R}$$

$$\frac{d R_g}{d r_1} = \frac{R - 2 r_1}{R}$$

R_g is maximum when $\frac{R - 2 r_1}{R} = 0$ or when $R = 2 r_1$

$$\therefore R_g \text{ (max)} = \frac{R}{4}$$

From this it will be seen that the usual high-resistance potentiometer, having a total battery circuit resistance of 20,000 ohms, introduces a variable resistance of 5,000 ohms into the galvanometer circuit and that the usual low-resistance potentiometer, having a total battery circuit resistance of 100 ohms, introduces a variable resistance of only 25 ohms into the galvanometer circuit.

Discussion

For discussion of this paper see page 1324.

Electrical Units and Their Application

BY L. T. ROBINSON*

Fellow, A. I. E. E.

INTRODUCTION

THE importance of measurements in any art or science is great; and progress is not made without measurement. Progress and improvement are made possible to the extent that those interested in and working along the line of developing and improving measuring methods and instruments are able to anticipate the needs of those interested in the development and operation of systems, devices, and apparatus.

Electrical units are based on or definitely related to units of length, mass, and time. In the ordinary sense these units are not electrical but because so much depends on these fundamental units; we must be interested primarily in how definite and permanent the fundamental units are and how precisely length, mass, and time may be determined by reference to existing standards; also how accurately copies of units may be made and the degree of precision attainable in producing for practical use multiples or submultiples of the fundamental unit chosen.

Probably the so-called c. g. s. system of units is most familiar. In this system the centimeter is taken as the unit of length; the gram as the unit of mass, and the second as the unit of time. This system has been quite generally accepted for many years. For some purposes it may be a little old fashioned but in general it is likely to endure for a long time. It may be better to say that *l*, *m*, and *t* are likely to be required as fundamental units in the future as they have been in the past. At this point it would be permissible to define *l*, *m*, and *t* but this will not be attempted. So many things have occurred within the last few years to upset older conceptions of what anything really is, that satisfactory definitions are not written down offhand. However, all those interested in electrical science and art have an idea of what these quantities mean, at least sufficiently for the present purpose.

Whatever is done, we may always retain the c. g. s. system, or something equivalent to it, and therefore be tied permanently to the fundamental units of length, mass, and time which have given evidence of being so reliable and permanent. Many determinations leading to the absolute value of the volt, ampere, and ohm have been made and these efforts have attained a large degree of success. However, the procedure by any methods that have been employed requires a very long time and infinite knowledge and pains and even then the precision arrived at is not all that could be desired. Easier and more satisfactory methods it is hoped may be discovered.

Before making any statements that may be useful for comparison, I would like to emphasize a point; *viz.*, that only very general statements will be made and comparisons will be based on groupings, each one roughly 10 times or 1/10 of the magnitude of the one next to it. A precision of 1 to a possible 9 parts in 100,000,000 will be called 10^{-8} and so on down to 10^{-2}, which will give a sufficient range. There will then be seven classes 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2} into one or another of which all things to be considered will be placed. It may well happen that some may feel that certain estimates are not correct even when referred to such wide limits.

We are usually quite satisfied in ordinary work with accuracy of standard and precision of comparison considerably below the best obtainable, but workers in the field of primary reference standards must of necessity be able to make determinations 10 to 100 times more precise than the precision demanded in practise so that the practical art has something to grow up to and its possibilities are not limited. Sometimes unusual practical requirements arise suddenly that can only be met with precision far greater than any previously employed.

It is in this region that national laboratories and some independent workers find a very useful field and in this field the national Bureau of Standards stands second to none. These groups should all receive every encouragement to go forward for it is not known when the advancing art will need much greater precision than has heretofore been attained.

C. G. S. UNITS

Mass standards are permanent and can be compared to a precision of one or at least a very few parts in 100,000,000 and standards of length about the same. These, therefore, lie definitely in the 10^{-8} class. Time, one of the fundamental elements in many things, can hardly be regarded as in the same class as length and mass.

There are 86,400 seconds in a day. Therefore a minimum departure from a uniform rate of about 0.001 second a day is required in order to have a clock included in the 10^{-8} class. This is better than has been attained over an extended period of time. Time is therefore in the 10^{-7} class. It even has a tendency to slip into the 10^{-6} class.

Roughly 500 years ago the first instruments that could really be called clocks were brought out and they were quite definitely in the 10^{-2} class, probably the lower end of this band; in 300 years they were brought into the 10^{-6} class; in about 150 years more into the 10^{-7} class. During the last few years the clocks

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*General Electric Company, Schenectady, N. Y.

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of Shortt and of Schuler, each quite different from the other, have given unmistakable signs of being able to qualify for the 10^{-8} class.

This shows remarkable progress. Twice within the last say 40 years the error in time keepers has been divided by 10.

This brief consideration of time is not really a digression for within the last few years the demand for accurate measurement of time on which frequency or wavelength measurements are based came almost too soon. This is a definite example of where we found ourselves too close for comfort to the precision maintainable in primary reference standards.

But the picture is not without its brighter side. The crystal oscillator, which in a certain way caused the trouble by requiring accurate adjustment and timing or which, to take the other point of view, had great value because it was capable of being given this fine adjustment, has been found to be a most reliable timing device itself. First checked with clocks it now bids fair to turn about and enter the higher time keeping class itself. Comparisons between crystal oscillators can now be placed in the 10^{-8} class and timing of crystals in the 10^{-7} class.

As a general statement it is fairly certain that a perfectly free pendulum is apt to be more certain in its performance than the motions of the planet on which we live but on the other hand observation of the action of crystal oscillators, treated with the same care and respect as precision clocks, seems to make it also fairly certain that no fault as to permanence or precision of performance is chargeable to the crystal itself. Sufficiently long periods of continuous operation have not been observed so that it would be perhaps unwise to be too sanguine of the final result, but we may have a time measurer that is more perfect than any pendulum can ever be because the oscillating crystal is not affected by gravity which may change some in any locality and because it is probably much more easily protected against shocks than a pendulum. On the other hand it is at present rather afflicted by complicated auxiliary apparatus which while it functions well leaves many chances for failure. Soon the motions of the earth may be checked by clocks or their equivalent instead of employing the present process of determining the clock rates from the relative motions of the earth and the stars. Irregularities in these motions may be shown by the clocks.

But why say so much about length, mass, and time? It is because it is of interest to know just about where we stand on these fundamental standards and the conclusion is that they are in a fairly satisfactory position; time far in the rear but rapidly advancing to a position of equality with the other two. I therefore feel that length, mass, and time are good things to tie to and start from. The difficulties seem to be in the steps necessary to realize electrical standards from length, mass, and time. Improvements may come and it is to be hoped that they will soon arrive so that the precision assignable to the fundamental units, length, mass, and time, may be more nearly realized in the electrical units that are used for fundamental reference.

ELECTRICAL UNITS

We are more directly interested in the ohm, the volt, and the ampere or the absolute units of which these are derived multiples. As will be seen later there is a very wide gap between the precision assignable to length, mass, and even time, and that assignable to the absolute values of the practical electrical units, for a very good reason. Fundamental length and mass standards are in a sense arbitrary. This does not give concern because the meter need not be exactly 1-10,000,000 of the polar quadrant of the earth and the gram may not have exactly the mass, of 1 cu. cm. of water at maximum density provided the established standards remain permanent. There is reason to believe that they are permanent within satisfactory limits. On the other hand in considering electrical units their relation to length, mass, and time must be known. They should not be arbitrary if agreement with mechanical units and others which are derived from length, mass, and time also is to be maintained. The electrical standards must therefore be kept from change and must also be brought into a definite and predetermined relation to the fundamental units; so that conversion factors are as simple as they can be. The necessary powers, roots, and 4πs are quite sufficient without the addition of odd values differing only a small amount from multiples of 10. From the way in which the art has developed the ohm and the volt or definite multiples of either are more readily available and transportable from place to place than is the ampere.

I believe that the ohm is now defined as the resistance at 0 deg. cent. of approximately 106.30 cm. of mercury, 1 sq. cm. section. This may be certain to five significant figures or 10^{-4}. It can hardly be said to be dependably known to six figures, 10^{-5}. However, work is constantly being done to better this situation. Copies and comparisons of resistances in general may be made to about 10^{-6} and the permanence of the primary reference standards is good, within about the same limits.

Therefore, it may be said that the ohm may be considered in a safe situation, but more certainty as to the absolute value would be desirable. I should like to see this unit known and its permanency and absolute value unquestioned to 10^{-6}. This seems quite possible of attainment. It may be that those working in this field will say that they have already arrived; if so, good. At any rate, gratifying progress has been made. Looking back to the first ohm of the British Association Committee it was about 1½ per cent smaller than the present ohm, and it has taken nearly

50 years to eliminate the greater part of this error, although most of this change was in one important step. Precision and permanence have just about kept out of the way of progress in the practical field.

The volt had rather a bad start for some time. The preference was to derive this from the ampere and the ohm. With much time and care galvanometers were constructed that depended for their accuracy on measurements of length and of the magnetic field of the earth. Again, we were tied up with a property of the earth as we are now with time, but unfortunately we cannot transmit amperes around the countries by telegraphic signal or by radio, and although the earth's magnetic field is capable of very precise determination, the ampere or multiples when realized could not very well be carried home and used. There was nothing to carry the ampere in or with. Instruments using no permanent magnet and which did not depend on the earth's magnetic field were made—electrodynamometers. Some were very good, but not always dependable or precise within the required limits.

Certain voltaic cells were known all along, but up to the advent of the Clark cell no competitor of the galvanometer or electrodynamometer appeared. With the advent of the Clark cell something was available which was a very great advance indeed. It could be reproduced in various localities with considerable precision. However, it had a considerable temperature error and it was very difficult to keep the containers sealed, also terminals cracked, necessitating the making up of new cells.

Enormous improvement was subsequently made by Edward Weston when his Standard cell was given to the world. And it is this cell in one form or another that is now used together with copies of the ohm and multiples as the basis of most electrical measurements.

How good are our volts and how permanent? I should say very nearly in the same class as the ohms, 10^{-4} class, and as a result the ampere in terms of these two standards may come perhaps in the same class. This refers to absolute values, the comparisons are probably possible to 10^{-6}.

A class of instruments for the determination of or the realization of ohms, volts, amperes, and watts, using standard cells and carefully compared resistances, are capable of giving multiples of the units throughout a wide range. I refer to the so-called bridges and potentiometers. By means of these instruments values within any reasonable range may be given and with precision well up into the 10^{-5} class. The instruments are convenient to use and including the portable or standard cells with which they are usually used are permanent and reliable. When it is considered that they are usually employed in the calibration of portable and working instruments the precision of which they are capable is for most purposes unnecessarily high. There is a still further class represented by the deflection potentiometer which is perhaps in the middle part of the 10^{-4} class.

These instruments may be used as reference standards and also for direct observations. In fact for continuous currents there is the opportunity at any time to secure definite and accurate results beyond, in most cases, the practical requirements.

TRANSFER TO ALTERNATING CURRENT

However, many measurements must be made where alternating current is the medium and here in special cases the instrument commonly used employs some sort of a reflecting device for observing with some precision the indications of the moving part. These instruments may be placed in the border line between the 10^{-3} and 10^{-4} class. They do not fill the requirements with complete success. Considering what is available for the intermediate class of work of which so much must be done, *i. e.*, between the 10^{-5} class and the 10^{-3} class, time and patience are surely taxed to get what is required. Agreement on this point may not be complete and I do not offer this comment as a criticism of anything that has been done. On the other hand I feel that we need something here that we do not have at the present time and the nearer it can be to a portable instrument the better. It should be quite definitely in the 10^{-4} class for volts, amperes, and watts. For other general measurements we have the well-known portable instruments capable of a precision of say 1 part in 500 or perhaps better if advantage can be taken of a group of readings; perhaps not as good as this if small scale readings are employed.

Something of the general class of the deflection potentiometer conveniently usable on alternating current would be very helpful. There is also to consider the step which has been taken from direct current to alternating current and which rests on the assumption that a given instrument will give the same indication on alternating current as it does on direct current for the same r. m. s. values. I am not sure that this step rests on a perfectly secure basis. By this I do not mean that reasonable security cannot be assured by applying suitable corrections but many times much is taken for granted.

Higher frequencies than 60 cycles must sometimes be reckoned with but we will not yet speak of this point. However, low power factor is a serious problem.

In using portable direct-reading instruments or instruments of the intermediate class on alternating current or on alternating-current systems it is sometimes difficult to realize the precision of which the instruments are capable because of slow pulsations in the supply source and because all moving systems have not the same time of swing. In fact, in passing into alternating-current work we are of necessity compelled to work on rotating machinery and this brings in more problems. Some success has been attained by recording photographically or by other means the position of the pointers of a group of instruments but this is not always satisfactory. It is usually best to record enough readings to overcome the effects of the fluctuations. Matters can be greatly improved in a well equipped laboratory by using very refined regulators on the supply lines. This is a great help but fills only a small part of the general need.

Many times we do not get all the precision out of portable instruments of which they are capable because we are apt to consider them as having no permanence of their own. It is common practise to compare portable instruments with a potentiometer or some other arrangement, say 10 to 100 times as precise, but not always anywhere near it, and reject all values found by previous comparisons. Almost any instrument is good enough to regard a previous comparison as having some weight. It is only a question of how much; it should not be neglected altogether.

In dealing with large values of alternating-current amperes, volts, and watts one usually cannot use the resistances so precisely comparable with reference standards. In this field it has become customary to employ instrument transformers. These transformers serve the purpose also of protecting the observer from contact with the circuit voltage. Instrument transformers are capable of quite precise work. They may be placed, when carefully checked and properly used, in the lower part of the 10^{-4} class.

Within comparatively recent years the electrical measurement art has required expansion into the high frequency field and also into the field of very low power-factor measurements which brings in a new set of requirements and in which very many curious effects must be guarded against. The recording of wave fronts which are expressed in microseconds together with a very great variety of problems which have come up in connection with sound and communication systems using wires and also the radio art have been for the most part met with a fair degree of satisfaction. This general group cannot be referred to in detail. A tremendous range of voltage current, power, and frequency must be covered, up to millions of volts and thousands of amperes and also millions of cycles per second and correspondingly small values.

Great increases in sensitivity and decreases in the amount of power required to make measurements have been made possible by the use of vacuum tubes and a large expansion in this field may be looked for. Permanence and reliability, if they could be increased, would avoid the necessity of using these methods in most cases for comparisons and placing no great reliance on permanence.

Capacitors or condensers are very useful devices as they are able to give out a definite quantity of electricity when charged with a voltage which can be determined very precisely from standard cells and suitable multiplying arrangements. It has not been my personal experience, however, that condensers are permanent and reliable to the same extent that resistors and standard cells are and improvements along this line would be desirable. For example, in magnetic measurements it would be much simpler to work from a reference standard condenser than to use mutual inductances determined by some of the well-known methods of comparison or by direct reference to length standards.

Materials for resistance standards have been greatly improved and it may seem that there is little need for further improvement. The accuracy with which comparisons can be made is perhaps ten times greater than the precision or permanence of resistance units assembled in practical apparatus without taking undue precautions which need not be taken if the temperature effects were even less than they are now.

The development of an increased class of instruments in the intermediate class (10^{-4}) is hoped for. The requirement is for something which will stand in the alternating-current field, at normal and if possible high frequencies and low power factor, in the same place that the deflection potentiometer, resistances, and standard cells stand to direct-current applications.

Very little advance among practical workers has been made along the line of combining and weighing of results and in the application of well-known and simple probability relations. It is possible to do much along this line and to develop a few simple relations which will cover most cases and which will be of enormous advantage in use. In fact, experience can develop an intuitive sense in this regard and it is surprising what can be done with comparatively crude apparatus if the results obtained with a number of determinations are made use of and sufficient care is taken to control the conditions under which the observations are made.

SUMMARY

It is not the intention that the conclusion which should be drawn from this brief review of the situation is that conditions are unsatisfactory. Of course, the point of view might be taken that we have not made satisfactory progress in the last fifty years and that the best reference standards are not at all in the same class with available standards of length, mass, and time.

Ordinary portable instruments seem very crude in comparison with portable and every day instruments for determining mass, length, and time. On the other other hand I think we should not regard the situation at all in this light. Length, mass, and time standards have had at least ten times as long a period of development. The one that has advanced the most is time. This advance has been about 100 fold in the past 40 years.

In the electrical field, reference standards in relation to the fundamental units, and the precision of comparison with reference standards have been increased in the same period by about the same amount. In the portable instrument field and in indicating instruments generally, I feel that errors have been divided by about 10. We can, therefore, review the situation with some degree of satisfaction. We have by comparison equalled the rate of progress in other branches but there is still much to be done and much to be learned by occasional excursions into other lines a little outside of the electrical field.

Most important of all we can feel assured that the interest in going forward is undiminished and that during the next few years further and important advances will be made.

Discussion

For discussion of this paper see page 1324.

The Unit of Electrical Resistance;

Past History and Impending Change*

BY H. B. BROOKS[1]
Fellow, A. I. E. E.

Synopsis.—In 1923 an amendment to the International Convention of 1875 relating to weights and measures gave the International Committee of Weights and Measures authority to deal with the electrical units. This committee was thereby confronted with two major problems concerning the magnitudes of the units and the best procedure for their legalization and maintenance. It set up an Advisory Committee of experts to advise it on all such questions. At its second meeting, in 1930, the Advisory Committee adopted a resolution to the effect that further comparisons of the manganin wire standards of resistance with mercury ohms are unnecessary.

The mercury ohm has so long been the legalized material standard of resistance that it is regarded by many workers as a permanent institution, subject only to such slight revision of the length and mass of the mercury column as might be shown to be necessary as the technique of absolute measurements becomes more accurate. The present paper first gives a background by outlining the entire history of the unit of electrical resistance. It then gives briefly the reasons why the mercury ohm is obsolescent, as follows: the technical difficulties attending its use are very great; determinations with it are useless unless a relatively large number is made with great pains by highly skilled observers; some of the factors entering the result (waviness of the bore of the tube, uncertainty regarding the terminal resistance) remain insoluble to the present; the mercury ohm was devised in the day of the individual worker, separated from his fellows by great difficulties of communication, and hence obliged to prepare his own standards from specifications; now great national standardizing laboratories issue the most accurate standards available, backed by legal authority. The mercury ohm has always been a necessary, expensive evil. It has held its place because it could be reproduced more precisely than the agreement between the results of absolute determinations of the ohm. The technique of absolute determinations has improved until now it may fairly be said to be at least on a par with the mercury ohm as to reproducibility. The laborious and time-consuming repetitions of mercury-ohm determinations may therefore cease, and the high-grade technical effort they would require may be more profitably spent in improving the technique of absolute measurements of resistance.

IN 1923 an amendment to the international convention of 1875 relating to weights and measures was proclaimed, containing the following provision:

> "After the (international) committee (of weights and measures) shall have proceeded with the work of coordinating the measures relative to electric units and when the general conference (of weights and measures) shall have so decided by a unanimous vote, the (international) bureau (of weights and measures) will have charge of the establishment and keeping of the standards of the electric units and their test copies and also of comparing with those standards, the national or other standards of precision."

The International Committee of Weights and Measures, having thus been given legal authority to deal with electric units, was confronted with two major problems; first, whether to maintain the accepted values of the units as nearly as possible, or to revise them to accord with the fundamental c. g. s. system; second, whether to maintain the mercury ohm and silver voltameter as legalized material standards to represent the units, or to legalize the absolute units themselves. In the latter case it would become the duty of the national standardizing laboratories, having the necessary equipment and personnel, to carry out such absolute measurements as might be necessary to fix the values of their working standards. This work would be done in cooperation with the International Committee. Whatever course this committee might follow, there was an evident need for the prosecution of intensive researches to provide the technical basis for final decisions on the type of standards and on the units to be adopted for international use.

In a paper before the summer convention of the A. I. E. E. in 1927, Mr. E. C. Crittenden discussed the status of the international electric units, particularly as maintained at the Bureau of Standards, and pointed out the urgent need for further investigations of the international standards and of the experimental methods for realizing the absolute units upon which they are based. The important questions raised in this paper were referred to the Institute's Committee on Instruments and Measurements for consideration. The subcommittee appointed to study the matter prepared resolutions urging the Bureau of Standards and foreign national standardizing laboratories to undertake, as soon as possible, the additional researches needed before suitable legislation to reduce the discrepancies between the international units and the absolute units can be enacted; and to carry out the further researches that will eventually make possible the legalization of the absolute units in place of the international units. In 1928 these resolutions were approved by the Standards Committee, adopted by the Board of Directors of the Institute, and transmitted to the appropriate committees of the United States Senate and House of Representatives, the Bureau of Standards and other national standardizing laboratories, and to the International Committee of Weights and Measures at Sèvres.

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*Approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

[1] Physicist, Dept. of Commerce, Bureau of Standards, Washington, D. C.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

To assure itself the necessary expert counsel in regard to the important electrical questions before it, the International Committee in 1927 had set up as a subsidiary an Advisory Committee on Electricity, with a membership limited to 10. Eight members were appointed, including: one representative each from the national laboratories of Germany, Great Britain, Japan, Soviet Republics, and the United States; one from the Laboratoire Central d'Electricité at Paris; M. Guillaume, Director of the International Bureau of Weights and Measures; and Professor L. Lombardi of the Royal School of Engineers at Rome. At its first meeting in Paris in 1928 the Advisory Committee passed resolutions which were adopted by the International Committee a year later. These resolutions stressed the importance of unifying the systems of electrical measurements on a basis free from all arbitrary characteristics, by the adoption of the absolute system of units derived from the c. g. s. system; and expressed the wish that to this end researches to fix with exactness the ratios between the absolute units and the international units then in use be pursued in suitably equipped laboratories.

The second meeting of the Advisory Committee on Electricity was held in 1930 at Paris. Those who have shared the feeling that legalized material standards, such as the mercury ohm, are permanent institutions, possibly subject to slight changes in specifications, but not to be superseded by legalized abstract units, will perhaps be surprised by the following resolution, the first of two adopted at this session:

> 1. "With regard to the unit of resistance, the ohm, considering that methods of determining the absolute ohm are sufficiently advanced and that the agreement between the measurements of the coils (secondary standards) of the different (national) laboratories remains within the limits of precision of the measurements, it is not necessary at present to undertake further comparisons of the resistance coils with mercury ohms."

In order to bring out the full significance of this seemingly radical proposal, and the sound reasons for the ultimate abandonment of the mercury ohm as a legalized material standard, it will be of interest to review the history of the ohm.

After the announcement, in 1827, by Ohm of his famous "law," electrical workers began to feel the need for a unit of electrical resistance. Nature had been kinder in the matter of standards of electromotive force, and the early workers could use the electromotive force of a Daniell cell or a gravity cell as a unit. Lenz, in 1838, suggested as a standard for the unit of resistance "one foot of No. 11 copper wire;" Wheatstone, in 1843, "one foot of copper wire weighing 100 grains." Buff, in 1847, proposed to use a German-silver wire 1.5 mm. diameter and 75 cm. long. Jacobi, in 1848, had a certain piece of copper wire as a material standard for his unit, and sent copies of it to other workers. The telegraph engineers were not idle. In England they introduced a unit which was the resistance of an English mile of No. 16 copper wire; in France, the resistance of a kilometer of iron wire 4 mm. in diameter was used; in Germany, that of a German mile of No. 8 iron wire. This does not exhaust the list of arbitrary standards of resistance.

All of these proposals were faulty. Simple metal wires were difficult to obtain in sufficient purity; also, their resistivity is affected by internal stresses and the degree of annealing. The alloy wires were not of definite and exactly reproducible composition.

The use of mercury as an ideal metal for the purpose seems to have been first suggested by Marie-Davy, but Werner Siemens, in 1860, made the first practical proposal concerning it, namely, that the unit of resistance should be "The resistance at 0 deg. cent. of a prism of mercury 1 meter long and 1 square millimeter in cross section." He demonstrated that he could reproduce a unit of resistance by means of mercury in glass tubes with an error of less than 5 parts in 10,000. The unit he proposed came into use under the name "Siemens Einheit" (Siemens unit), denoted in the older literature by the abbreviation "S. E."

In 1861, at the suggestion of Sir Wm. Thomson (later Lord Kelvin) the British Association for the Advancement of Science appointed a Committee on Standards of Electrical Resistance. The original committee of six members included Prof. Wheatstone and Dr. Matthiessen. Other outstanding men added during the first eight years included Maxwell, Carey Foster, Latimer Clark, and Joule. Other names which appear later are those of Ayrton, Perry, Rayleigh, Oliver Lodge, Muirhead, Preece, Fleming, Glazebrook, J. J. Thomson, J. V. Jones, Silvanus P. Thompson, Mather, and F. E. Smith.

The "B. A. Committee" recognized that under the conditions then existing it was necessary to have material standards of resistance, but it wanted them to refer ultimately to an absolute basis. Thomson proposed as the basis the foot-grain-second system; Weber and Gauss, the millimeter-milligram-second system. The Committee finally adopted the centimeter-gram-second system. Because of the high precision (1 in 100,000) with which two nearly equal resistances could be compared, and the great scattering (about 10 per cent) between the results of absolute measurements of resistance by various observers, the Committee adopted as one of its cardinal doctrines the idea that a material standard should be developed, to have a value as nearly as possible equal to that of an ideal absolute unit; that this standard, once made, was to be regarded as a prototype standard, never to be changed even though succeeding absolute measurements might show it to be appreciably in error.

Three members of the Committee made absolute measurements of resistance at King's College, in 1863 and 1864, by rotating a short-circuited coil of copper wire, about a vertical diameter and with a measured velocity, and observing the resulting deflection of a magnetic needle at the center of the coil. From the known angular velocity, the deflection of the magnet, and the linear measurements of the coil, the resistance of the coil in absolute units was computed. On the basis of this work, the Committee constructed standard coils of platinum-silver wire, and began to issue copies of the "B. A. Unit." The Committee was dissolved in 1870 without having established a unit for either electromotive force or current.

In 1878 the investigations of Rowland at Baltimore showed that the B. A. unit was more than 1 per cent smaller than the value (10^9 c. g. s. electromagnetic units) which the B. A. Committee had intended to give it. This result was verified soon afterward by other investigators.

In 1880 the B. A. Committee was reappointed. In its reports during the next few years it was brought out that as the B. A. unit was known to be over 1 per cent in error, the question of whether to maintain this unit indefinitely or to define the ohm as 10^9 c. g. s. units might well be reconsidered. In the meantime a number of mercury standards of resistance had been set up in accordance with the proposal of Werner Siemens. The agreement between these was satisfactory from the standpoint of that time, and the results of absolute determinations had consequently been referred, directly or indirectly, to the Siemens Unit.

In 1881, at the invitation of the French Government, an International Congress of Electricians met at Paris for the purpose of establishing definitions of the electrical units in a form suitable for enactment into legislation. This Congress adopted resolutions proposing: that the ohm and the volt preserve their previous definitions, namely, 10^9 and 10^8 c. g. s. electromagnetic units, respectively; that the ohm be represented by a column of mercury 1 square millimeter in cross section, at a temperature of 0 deg. cent.; and that the ampere be defined in terms of the ohm and the volt. The coulomb and the farad also were defined. The Congress proposed that an international commission be charged with the determination, by new experiments, of the *length* of the mercury column to have a resistance of 1 ohm; that is, 10^9 c. g. s. electromagnetic units of resistance. This commission, the International Conference for the Determination of the Electrical Units, at its first meeting in Paris in 1882, decided that definite action should be deferred until further absolute measurements could be made.

In 1883, coils sent in to be tested by the B. A. Committee were certified in B. A. units, with an alternative figure in "R. ohms" (real ohms) on the basis of 1 B. A. unit equal to 0.9867 R. ohms. In 1883 the British Association granted funds to its Committee on Electrical Standards for the purchase of "Standards of resistance in terms of the (real) ohm." The purchase of these standards was deferred to await whatever action might be taken at the second meeting of the International Conference for the Determination of the Electrical Units. At this second meeting, held in 1884 at Paris, this Conference adopted 106 centimeters as the length of the mercury column, in spite of the fact that the best absolute determinations indicated that the correct length was very close to 106.3 centimeters. This compromise with the facts was made because it was considered advisable for a provisional value to be correct to the last figure given. The unit of resistance so defined was given the misleading name "legal ohm," but although it was used to some extent, it was never legalized.

The B. A. Committee indirectly defined the relation between the B. A. unit and the "legal ohm" by stating that the resistance at 0 deg. cent. of a column of mercury 100 cm. long and 1 sq. mm. cross section was equal to 0.9540 B. A. units. Thereafter, coils sent to the B. A. Committee's laboratory for test were reported in legal ohms, with a supplementary statement of the value of the legal ohm in B. A. units.

The B. A. Committee's reports of 1888 to 1892 reveal increasing doubts and difficulties because of variations in the relative values of their wire standards. In the attempt to explain some of these changes some improbable assumptions were made; for example, that in some way the nameplates of two of the coils had been interchanged, and that previous observers had used wrong values of temperature coefficient. (These difficulties, in the light of today, are explicable on the basis of the bad practise then followed, namely, the embedding of the windings in a mass of solid paraffin, which material has at least two serious drawbacks; an extremely high expansivity and a very low thermal conductivity.) These difficulties effectually negatived the Committee's original plan for a wire standard never to be altered, and established the fact that some independent and reliable method for checking the constancy of the wire standards was urgently required.

In 1892 the B. A. Committee announced that it had discontinued issuing standards in terms of the legal ohm in favor of the ohm defined as the resistance of a column of mercury 106.3 cm. long.

The 1893 report of the B. A. Committee contained an appendix by Prof. J. V. Jones describing his Lorenz apparatus for the absolute measurement of resistance and giving the results of some measurements made with it. He states that "Such an apparatus placed in the National Laboratory might with advantage be kept in constant use, not only for the calibration of low resistances, but also as embodying in concrete form a proper ultimate standard of electrical resistance." In an appendix to the 1894 report Prof. Jones communicates the result of a determination of the ohm in absolute measure with his Lorenz apparatus. He obtained 106.32 cm. as the length of a mercury column

1 sq. mm. in cross section having a resistance of one "true ohm."

An international electrical congress met in Chicago during the Exposition of 1893, with representatives of ten governments in attendance. It adopted resolutions defining eight electrical units. To distinguish them from their predecessors, they were called the *international* ohm, international ampere, etc. The international ohm was "*based upon* the ohm equal to 10^9 units of resistance in the c. g. s. system of electromagnetic units, and is *represented by* the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice 14.4521 grams in mass, of a constant cross-sectional area and of the length of 106.3 cm."

Because of certain defects and inconsistencies in the resolutions of the Chicago Congress, the six national governments which afterwards legislated on the matter defined the electrical units in different ways. One of the outstanding defects of the Chicago resolutions was that the ohm, ampere, and volt, which are physically related by Ohm's law, were all defined in terms of material standards.

The inconsistencies of the resolutions of the Chicago Congress were not recognized when the U. S. legislation (Act approved July 12, 1894) was enacted. They were recognized in the German law of June 1, 1898, which defines the ohm in terms of a column of mercury, the ampere in terms of a rate of deposition of silver, and the volt in terms of the ohm and the ampere. At the call of the German Reichsanstalt, an international conference was held in Berlin in 1905, at which this logical procedure was recognized as the correct one. The Berlin conference also favored replacing the Clark cell by the Weston normal cell.

In 1908 an international conference on electrical units and standards was held at London, with delegates from 21 countries in attendance. At this meeting resolutions were adopted which for the first time clearly differentiated between the fundamental (absolute) electrical units and a system of units representing the fundamental units, and sufficiently near them for practical use and to serve as a basis for legislation. The London Conference recommended the adoption as this second system, of the international ohm defined in terms of a mercury column, the international ampere defined in terms of a time-rate of deposition of silver, and the international volt and international watt defined in terms of the international ohm and international ampere. The Conference provisionally adopted the value 1.0184 international volts as the electromotive force at 20 deg. cent. of the Weston normal cell.

In 1910 an intercomparison of Weston normal cells and of silver voltameters was carried out at the Bureau of Standards by members of that institution together with one delegate each from the national standardizing laboratories of England and Germany and one from the Laboratoire Central d'Electricité of Paris. As a result of this work it was agreed to define the electromotive force of the Weston normal cell at 20 deg. cent. as 1.0183 international volts. This value was officially recognized by the Bureau of Standards on January 1, 1911, and is still in force. The international ohm was taken to be the mean of the values realized by the use of mercury ohms at the national laboratories of England and of Germany, as represented by manganin coils brought by the representatives of these institutions.

Mercury standards of resistance had been constructed by F. E. Smith at the English National Physical Laboratory during the years 1902 to 1907. A preliminary calibration of 70 glass tubes gave the data on which 11 tubes of the greatest possible uniformity of bore were selected. This matter of uniformity of bore is very important. The legal specifications assume a column of mercury of unvarying cross section, which cannot be realized. In practise, after selecting the most uniform tubes, a prolonged experimental study of the irregularities of bore is followed by a mathematical analysis to determine the "caliber correction," which is the factor by which the resistance of the column of mercury of variable cross section is greater than the resistance of an ideal column of mercury having the same length and mass, and an absolutely uniform cross section. It is desirable that this factor be as nearly unity as possible. The calibration factor of Smith's tubes exceeded unity by from 8 to 200 parts per million.

The elaborate technique of cleaning, calibrating, and cutting off the tubes, and measuring their length; of determining the mass of contained mercury; and of comparing the resistance of the tubes with the existing wire standards, is too laborious and involved to be outlined here. To be worth doing at all, this technique must be carried out by scientific men of great manipulative ability, with the observance of extreme precautions against errors in various parts of the measurement. The amount of time required is very great; so much so that in spite of the legal standing of the "mercury ohm" only a relatively small number of outstanding determinations have been made during the past thirty years.

Smith's final result was that the unit which had been in use at the National Physical Laboratory was 85 parts per million lower than the international ohm as realized by his mercury standards, and 19 parts per million lower than the international ohm as maintained at the German Reichsanstalt.

Smith's account of his work is notable for its frankness and freedom from bias. He seems to be the only worker in this field to appreciate and to discuss a source of error not even mentioned by the rest. The measured "length of the tube" which has been so carefully determined with all possible accuracy is actually the length between the end faces of a hollow glass body of approximately cylindrical form. The length which ought to be measured is that of the axis of the column of mercury which fills this hollow cylinder, which length must be greater than the measured distance between the ends of the tube. Even today there is no known method for determining the true length of the mercury column. Smith carried out a calculation which showed that a waviness of the axis of the column, so slight that if the axis were drawn as a line it could not be distinguished by eye from a straight line, would introduce an error of 36 parts per million.

Seven mercury-ohm investigations have been carried out at the German Reichsanstalt. Of these, that of Lindeck, reported in 1891, must be regarded as preliminary only, because of the lack of various precautions not appreciated at that time. The work begun by Kriechgauer, completed and described by Jaeger in 1895, was much more thorough in nature, but included only two tubes carried to completion, and three others begun. The two completed tubes (No. XI and No. XIV) were not of very uniform bore; their caliber factors, before cutting to length, were respectively 1.002980 and 1.001731. By choosing the most favorable locations for cutting off the surplus end portions, the caliber factors were reduced to 1.001878 and 1.000341 respectively. Four 1-ohm manganin standards, employed in this work, have played a very important role in the maintenance of the unit of resistance at the Reichsanstalt. Their relative values have been accurately determined at frequent intervals, for over 30 years, and all the mercury standards since made at the Reichsanstalt have been compared with them. From a study of the relative values of these four manganin coils the Reichsanstalt has felt justified in assuming that their *mean* value may be taken to be constant over a period of years between mercury-ohm investigations. In fact, this mean value has continued to be taken as the basis on which resistance standards have been certified by the Reichsanstalt, even though succeeding mercury-ohm investigations have indicated an average increase in the unit (as maintained by the mean of the four coils) of about 1 part per million per year. This procedure has been considered warranted by the resulting convenient continuity in the records.

Other mercury-ohm determinations at the Reichsanstalt, which cannot be discussed here in detail, are listed in the following table:

TABLE I

Investigation No.	Observers	Date of publication
3	Jaeger and Kahle	1900
4	Jaeger and Diesselhorst	1904
5	Jaeger and Diesselhorst	1905
6	Jaeger and von Steinwehr	1913
7	von Steinwehr and Schulze	1927

The work of von Steinwehr and Schulze, presumably the last investigation of this kind that will be made at the Reichsanstalt, revealed the fact that some of the older tubes had changed their linear dimensions appreciably. For example, tubes XI and XIV, originally agreeing to 7 parts per million, had drifted in 12 years until they differed by 70 parts per million. Furthermore, the agreement between these old tubes and five newer ones was not very satisfactory. It is impossible to make an accurate check of the caliber correction factor of a tube after the end portions have been cut off. The dimensional changes can be confirmed by remeasuring the length of the tube and redetermining the mass of mercury required to fill it.

Four mercury-ohm tubes were constructed by Benoit in 1884. The length of the tubes appears to have been measured with great care, but the account of the electrical technique is too meager to permit an evaluation of the accuracy of the final results. In 1908 Benoit made ten tubes, but his account is not sufficiently detailed to allow a comparison between his results and those of the national laboratories.

In 1911-12 four mercury standards were made at the Bureau of Standards by Wolff, Shoemaker, and Briggs. The technique in general was similar to that of the Reichsanstalt. The 1-ohm manganin coils with which the tubes were compared were of the sealed, oil-filled type developed by Rosa. The results of the work showed that the international ohm as defined by the mean of the four tubes was 26 parts per million smaller than the international ohm as maintained by the Bureau's wire standards, 30 parts per million smaller than the unit as defined by the German tubes, and 20 parts per million smaller than the unit defined by the English tubes.

Five mercury-tube standards were made at the National Physical Laboratory for the Electrotechnical Laboratory of Japan, and five additional standards were made at the latter institution. The work was described in a report by Obata in 1914. The results showed a good agreement between the individual tubes, and between the mean of the five tubes made in the Japanese laboratory and the mean of the five made in England.

The principal advantages of the mercury-ohm standard are as follows: The conducting material is free from internal molecular stresses, and is purifiable to a high degree. Because it can be reproduced from specifications, the mercury-ohm standard serves to record the unit of resistance of any given period, within a few parts in 100,000, for future reference. The standard is simple in principle of construction, but its numerous drawbacks have caused it to be much neglected for many years, even in countries which have legalized it.

The disadvantages of the mercury-ohm standard are as follows: The conducting material has a high temperature coefficient of resistance, which in conjunction with the high thermal resistivity of glass makes it difficult to measure the temperature of the mercury with sufficient exactness, and limits the allowable test current through the mercury column to a small value.

It is now known that mercury is not a simple substance but a mixture of isotopes. (This is not a serious objection from the practical standpoint, because the particular mixture of isotopes of mercury found in nature seems to be very closely the same everywhere.) The mercury is liable to slight contamination from the metal electrodes immersed in it. The glass tubes cannot be made straight and of uniform bore, and the error arising from waviness of the bore, though of known sign, is of undeterminable magnitude. The terminal bulbs which are necessary to make connection to the ends of the mercury column introduce an uncertainty because no method has yet been found for definitely calculating the terminal resistance with sufficient accuracy. This fact makes it necessary to adopt an empirically chosen size of end bulb. The wires which lead the current into the terminal bulbs must be small so as to minimize the conduction of heat to the mercury; they are therefore of relatively high resistance, which is a drawback in some methods of effecting the electrical comparisons.

It is of interest to summarize some of the other major reasons for the original adoption of the mercury ohm and its present obsolescence. It was originally proposed at a time when electrical workers were much isolated. The existing means of communication were slow and imperfect, and hence each worker felt the need of preparing his own standards. Although the underlying absolute electrical units were recognized from the beginning of the B. A. Committee's work, the crudities of the apparatus and technique of absolute measurements resulted in such a scattering of the values obtained by means of them, as to constitute an imperative reason for a physical standard of resistance reproducible from specifications.

The situation has altered greatly since the beginning of the present century. The technique of the mercury ohm was almost fully developed at the start, having been originated and perfected by the thermometer maker, the physicist, and the chemist. In spite of the vast amount of high-class technical labor which has been expended on the mercury ohm, it seems physically impossible to push its limit of reproducibility beyond that attained thirty years ago, namely, a few parts in 100,000. On the other hand, the technique of absolute measurements has continuously improved until now it can fairly be said to be at least on a par with the mercury ohm as to reproducibility. The day of the isolated worker, setting up his own standards, has passed, and great national standardizing laboratories now not only establish standards with an accuracy beyond the resources of most individual workers, but have a legal status which gives the stamp of authority to their certified values. These national laboratories keep in touch with one another by the exchange of standards, thus securing a measure of international uniformity.

The technique of absolute measurements can undoubtedly be improved. But even if it could do no more than maintain its present parity (as to reproducibility) with the mercury ohm, the latter, always a necessary evil, has no further reason for existence.

It is beyond the scope of this article to give more than the briefest reference to absolute measurements. The spinning coil of the B. A. Committee has already been mentioned. The Lorenz apparatus is an elementary dynamo in which a non-magnetic metallic disk is rotated within the magnetic field of two solenoids wound on non-magnetic cores and traversed by a steady direct current from an external source. The apparatus thus constitutes a sort of homopolar generator in which an electromotive force is induced radially in the rotating disk. At a certain definite speed this induced electromotive force will just balance the $I R$ drop between the potential terminals of a four-terminal resistance standard through which passes the steady current circulating in the solenoids. From the accurately determined speed of rotation and the mechanical measurements of the dimensions of the disk and of the field coils, the resistance of the standard between its potential terminals can be determined in terms of the c. g. s. absolute electromagnetic unit. The most outstanding Lorenz apparatus thus far built is the one at the British National Physical Laboratory.

An absolute apparatus, simpler in some respects, is used at the German Reichsanstalt and at the Bureau of Standards. It employs single-layer solenoids wound upon accurately machined cylindrical forms of non-magnetic material, such as marble. The self inductance of such a coil, in terms of the fundamental units, can be computed with high accuracy from measurements of its dimensions. The self inductance can also be measured in terms of the international ohm and the second by means of alternating-current methods, using currents of which the frequency is accurately known. From the two results one may derive the ratio of the international henry to the absolute henry, equal to 10^9 c. g. s. units of inductance. It may be shown that this ratio (which is 1.00052, plus or minus a few units in the last place) is also the ratio of the international ohm to the absolute ohm. The results obtained by this a-c. method are in close agreement with those obtained with the Lorenz apparatus. These two methods do not exhaust the list of possible means for the realization of the absolute ohm.

It would be premature to attempt to set even an approximate date for the establishment of the absolute electrical units on a legalized basis, but there are urgent reasons for reaching this goal as soon as possible. The rapid development of electrical technology in recent years has imposed new and exacting demands for accuracy of measurement and permanency of standards. Nowhere is this demand more impressive than in some phases of the radio art, where (for example) frequency measurements are carried out and standards of frequency have been developed to an accuracy (a few parts in ten million) so great as to threaten to expose the failings of even the most highly developed timekeepers used in observatories. The world-wide sweep of radio makes *international* uniformity of frequency standards an imperative necessity. Electrical standards of various kinds, embodying the errors known to exist in the present units, are being made and distributed more widely than ever. The longer the legalization of the absolute units is deferred, the more costly and troublesome will be the necessary readjustment of the standards used in engineering and science when such legalization is ultimately accomplished.

Discussion

INTERNATIONAL STANDARD OF ELECTROMOTIVE FORCE

(Eppley)

DESIGN OF POTENTIOMETERS

(Stein)

ELECTRICAL UNITS AND THEIR APPLICATION

(Robinson)

THE UNIT OF ELECTRICAL RESISTANCE

(Brooks)

H. B. Brooks: Dr. Robinson's paper gives a valuable general survey of the electrical units and of the fundamental units and standards upon which the electrical units and standards are based. I am especially pleased to note his conviction that the electrical units should not be arbitrary if agreement with the fundamental units is to be maintained. This is in harmony with one of the resolutions of the Advisory Committee on Electricity at its first meeting in 1930, namely, that it is desirable to establish the electrical units on a basis free from all arbitrary character. This thought is not as recent as it may seem. At the International Conference on Electrical Units and Standards in London in 1908, the chairman (Lord Rayleigh) characterized the mercury ohm as a fifth wheel to the coach, and expressed the hope that in time it might be eliminated from the definition of the ohm. Dr. F. E. Smith, who did outstanding work on the mercury ohm years ago at the British National Physical Laboratory, expressed a firm conviction later that the time was ripe for the adoption of the absolute ohm in place of the arbitrary mercury ohm.

Dr. Silsbee and I were much interested to note Dr. Robinson's requirement for "something which will stand in the alternating-current field, . . .in the same place that the deflection potentiometer, resistance, and standard cells stand to direct-current applications." We have felt this need very clearly and Dr. Silsbee has had under development for some time a type of instrument which we hope may meet this demand. We have named the type "composite-coil instruments" although they operate directly on the electrodynamic principle. They can be wound as wattmeters, ammeters or voltmeters, and have a reading error equivalent to that of a pointer instrument having about 1,250 scale divisions. The unavoidable cost of this precision lies in the complication of supplying an auxiliary direct current and standard cell, and in somewhat less convenience in reading. A description of this type of instrument will be published shortly.

Dr. Eppley's paper is a very inclusive and carefully prepared treatment of the standard cell. Standard cells as everyday tools have become so customary that we seldom realize either the vast amount of research work which has been spent on them, or the distressing situation of the art of electrical measurements if the standard cell or an equivalent device should cease to be available.

My comments refer to the use of standard cells and to means for comparing them. I am very partial to the opposition method, in which one actually measures only the small difference between e.m.f. of the cell under test and that of the reference cell. Relative values to one part in a million are easily obtained in this way, provided one takes extraordinary pains to eliminate parasitic e.m.f., and yet the actual measuring device needs to have only moderate accuracy. I have under design a special potentiometer for standard-cell comparisons which is based on the opposition method but has novel features which avoid the two small inconveniences of the method, mentioned by Dr. Eppley. The observer need not determine whether the e.m.f. of the cell under test is higher or lower than that of the reference cell. The usual addition or subtraction is not required; the value of e.m.f. of the cell under test may be read off directly to the nearest microvolt, with interpolation to 0.1 microvolt. An exact balance can always be obtained, within the limit set by the sensitivity of the galvanometer used. Methods in which the microvolts figure (even tens of microvolts, in one prominent laboratory) is obtained by interpolation of two opposite galvanometer deflections are (in my opinion) objectionable in cases where the highest accuracy is desired. In such cases, the passing of even very small currents through the cell should be avoided as much as possible.

In the electrical instrument laboratory of the Bureau of Standards unsaturated cells for ordinary purposes are kept in heavy copper cases covered with heat-insulating material. These two expedients tend to prevent two undesirable thermal conditions; namely, inequality of temperature of the two limbs of the cell, and abrupt changes of the temperature of the cell as a whole.

I should like to recommend to users of unsaturated standard cells that they occasionally measure and record the internal resistance of their cells. Occasionally, gas bubbles may develop in the amalgam limb, and as the bubble grows in size the internal resistance of the cell increases. In time, the internal resistance may become practically infinite, and the cell useless. I have reconditioned such cells by carefully passing the amalgam limb back and forth through the flame of a bunsen burner. The heating of the entrapped gas drives it up in minute bubbles past the stopper which serves as a septum. Such cells have had their value of e.m.f. disturbed only temporarily by this process, and are useful after a reasonable period of rest.

To determine the internal resistance of a standard cell, it may be connected in opposition to a similar reference cell and the small difference of e.m.f. measured. If a resistance of one megohm (strictly, 1.018 megohm) is now connected across the cell under test, a new balance must be made because the potential difference at the cell terminals is lowered by the flow of one microampere through its internal resistance. Then the observed drop of e.m.f., in microvolts, is numerically equal to the internal resistance of the cell in ohms.

Mr. Stein's discussion of the factors affecting potentiometer design brings out the great importance of having the "internal resistance" of the potentiometer suitable for the constants of the galvanometer appropriate for the given measurement range. Formerly, this matter was not appreciated, but at present it is beginning to receive attention. However, in considering the matter of adapting the internal resistance of the potentiometer to that of the galvanometer, one should not feel obliged to obey too literally the old tradition which requires these two values of resistance to be as nearly equal as possible. It has been found independently by A. Schuster and myself[1] that the resistance of the galvanometer may differ very greatly from that of the rest of the circuit without the loss of a proportionate amount of working sensitivity. For example, if the resistance of the galvanometer coil is 100 ohms, the greatest "working sensitivity" will be had if the resistance of the potentiometer (including resistance of galvanometer suspensions and that of any other inert parts of the galvanometer) is also 100 ohms. However, the same galvanometer may be rewound with wire of the same space factor to give a coil of from 20 ohms to 500 ohms resistance, with a loss of working sensitivity nowhere in excess of 26 per cent of the optimum sensitivity.

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[1] A. Schuster, *Philosophical Magazine*, 39, 1895; p. 175; H. B. Brooks Bureau of Standards *Journal of Research*, 4, 1930, p. 297.

In discussing the relative stability of low resistance and high resistance coils, it should be remembered that this matter, as regards the potentiometer, is very different from the same question as related to most other apparatus composed of resistance coils. Absolute stability in the coils of a potentiometer is unnecessary; all that is required is that the various coils of any given potentiometer shall maintain their relative values to a suitably high degree.

Mr. Stein speaks of taking account of parasitic e.m.f. by using a false zero-setting of the galvanometer. There are cases, such as in the comparison of standard cells, where this method is not reliable. A much better plan is to use a compensating device consisting of a copper-wound slide rheostat with its winding in the galvanometer circuit. A flashlight cell or similar small cell sends a current of about 0.1 milliampere through a resistor of about 15,000 ohms to a tap from the center of the copper winding. The slider of the rheostat completes the circuit to the cell. This device may be cheaply made and provides the best known way of taking care of parasitic e.m.f.

It is pleasing to see Mr. Stein call attention to the possibility of parasitic e.m.f. in the galvanometer, of as much as 5 or 10 microvolts. Some workers in the field of precise measurements are very reluctant to believe this. Under a very unfavorable combination of poor design and exposed location of galvanometer, winter weather, and heating by circulated warm air, I once observed a parasitic e.m.f. in the galvanometer of 40 microvolts.

While the relative speed of working with the deflection potentiometer does not constitute a striking advantage for the very occasional test of an instrument, it becomes important in the production of instruments, or in the checking of large numbers by users. The greatest advantage which the deflection potentiometer possesses, as compared with the laboratory standard deflection instrument, is that on the average about 98 per cent of its reading is based on the e.m.f. of the standard cell. An operating advantage of the deflection potentiometer, of some importance, is that it is difficult to bend the pointer of its galvanometer, and easy to replace the galvanometer if it should be damaged. The bending of the pointer of a laboratory standard instrument is a much more serious matter, and causes a relatively long delay in getting the instrument back into service.

H. W. Bearce: An important step in the direction of increasing accuracy of length measurement was that taken in 1927 by the International Committee of Weights and Measures by which a supplementary definition of the meter was set up in terms of light waves. The provisional equivalent was established as 1 meter equals 1553164.13 wavelengths of the red radiation from cadmium under specified standard conditions. This relation already has found extensive use in a wide variety of interferometric apparatus.

L. T. Robinson: It is pleasing to note that as far as the ohm is concerned Dr. Brooks is in accord with the idea that the primary reference standard should be the absolute determination rather than any arbitrary standard. I did not know of the results of the work of the Advisory Committee on Electricity nor of Lord Rayleigh's earlier statement. These statements and other references by Dr. Brooks indicate that the fact is quite generally appreciated that the adoption of the absolute ohm in place of the arbitrary mercury ohm is near at hand.

The degree of precision that has been attained by the Bureau of Standards in the absolute determination of the ohm is most gratifying and indicates that the ideals set down in my short paper are possible. I hope that some equally satisfactory arrangement may be made with regard to the volt.

The figures given in my paper were arrived at only by considering the needs and to obtain accuracies comparable with those of the fundamental standards. Any misgivings that I may have had have been dispelled by the papers and discussions at this session.

The instrument that Dr. Brooks and Dr. Silsbee have under development to fill the gap in the alternating current field is very interesting. If application of the first type produced is limited by some complications I am sure that once the need is fully recognized and the precision demanded is met any minor difficulties and complications will soon disappear.

In Dr. Eppley's carefully prepared and instructive paper the fact is also quite clearly brought out that the permanence of standard cells is much more satisfactory than their reproducibility in absolute values. If the absolute value of the ohm and the volt is adopted and if such satisfactory progress is made with the volt as has been reported by Dr. Brooks with reference to the ohm, the requirement for working reference standards becomes only that they be permanent and transportable. The absolute values relating to any particular copy may be accurately determined and affixed.

Several minor comments occurred to me during the reading of Mr. Stein's paper. Referring specifically to page 1304 "parasitic e.m.fs." the figures given in the paper seem high. In the dial type potentiometer with which I am most familiar these parasitic e.m.fs. do not exceed 2 microvolts and are usually less than one microvolt total for all the dials.

Mr. Stein has spoken of high resistance and low resistance potentiometers and of the advantages of the low resistance type as far as the galvanometer is concerned. Perhaps any failure to agree with the author on all his conclusions may be that most users have associated "low resistance" in their minds with instruments having slide wires.

A dial potentiometer having about 100 ohms per volt seems best and this is quite satisfactory with commercial galvanometers.

Mr. Stein shows in Appendix 3 that within reasonable limits the galvanometer requirements for potentiometers is about the same whatever the resistance.

The best performance in the higher resistance galvanometers is limited by the very large number of turns required and the consequent small space factor of the winding. On the other hand the low resistance type is limited in the very low resistance range by the resistance of the suspensions becoming such a large part of the total galvanometer circuit.

I think all the well appreciated advantages of the 20,000-ohm potentiometer can be and in fact have been realized in the dial type of about 200 ohms.

H. L. Curtis: Dr. Brooks has shown the weaknesses of the mercury ohm and indicated the intention of the International Committee to adopt the absolute ohm as the unit of electrical resistance. He has asked me to summarize the information on the absolute ohm that probably will be available to the International Committee at its next meeting in 1933.

There are only two published results which are now of importance in deciding on the difference between the present international ohm and the absolute ohm. One of these researches was completed in 1913 at the National Physical Laboratory (F. E. Smith: *Phil. Trans. Roy. Soc.*, 214, p. 27, 1913). The experimental work for the second was completed in 1914 at the Physikalisch-Technische Reichsanstalt (Grüneisen and Giebe, *Ann. der Physik*, 368, p. 179, 1920) but was not published until 1920.

There is now in progress a determination by a second independent method at the National Physical Laboratory and two entirely independent methods are being worked on at the Bureau of Standards. The Bureau of Standards is also concerned with a third method, which is being done partly at the Bureau and partly at the Bell Telephone Laboratories, Inc., of New York City.

The result obtained by the National Physical Laboratory was:

One international ohm (NPL) = 1.00052 ± 2 absolute ohms

The result obtained by the Physikalisch-Technische Reichsanstalt was:

One international ohm (PTR) = 1.00051 ± 3 absolute ohms

However, there was a comparison of standards between the Physikalisch-Technische Reichsanstalt and the National Physical Laboratory in 1914 which shows that:

One international ohm (PTR) = 1.00003 international ohm (NPL) or a difference of three parts in 100,000. Hence

One international ohm (PTR) = 1.00051 ± 3 absolute ohms (PTR)
= 1.00055 ± 2 absolute ohms (NPL)

The difference between the two absolute determinations is four parts in 100,000, which can be accounted for by the experimental errors in the determinations.

Although the Bureau of Standards has not published any detailed description of its determinations, a preliminary result was announced by Curtis, Moon and Sparks at a meeting of the National Academy of Sciences in April, 1930. This result was:

One international ohm (B.S.) = 1.00053 absolute ohms

Although this result agrees very satisfactorily with those quoted above, which were obtained 15 years earlier in the national laboratories of England and Germany, it should be emphasized that the agreement may be partly accidental, because it is not possible to determine, with an accuracy of one part in 100,000, the relations between the units of resistance now used by these laboratories and those used by them 15 years ago.

Based on present information, a resistance unit can be established which will differ from the absolute ohm certainly by less than one part in 10,000, and probably by only a few parts in 100,000. Before the 1933 meeting of the International Committee, additional results may become available. It is to be hoped that sufficient data will be at hand so that some definite action can be taken at that time.

W. B. Kouwenhoven: The use of potentiometers and standardizing equipment by utilities companies is becoming common, and today many companies have one or more Weston Standard cells. They note that the e. m. f. of these cells varies from day to day. These variations are caused by unequal temperature changes, as pointed out by Mr. Eppley. Most of these company laboratories are not in a position to justify the expense of installing equipment to maintain their cells at a uniform temperature. I have found that a simple inexpensive and fairly satisfactory solution of the problem may be obtained by protecting the cells with heat insulating material. A two-inch layer of cork gives good results.

G. Thompson: Mr. Stein's very able paper on potentiometers draws merited attention to a measuring instrument which, with the wheatstone bridge, ranks among the most precise measuring devices of any field of science. It is capable of making measurements with a precision better than one part in 10,000 using the most ordinary precautions, and with an amount of care equal to that given to precise instruments in other fields, will yield results reliable to one part in 100,000, comparable to the precision obtained with a good chronometer, theodolite or precision surveyor's tape. Designed in the early days to make measurements of voltage of the order of one volt, the potentiometer is now being employed more and more for the precise measurement of voltages of the order of 0.1 and 0.01 part of a volt. For this latter class of measurements potentiometers having a resistance as high as 10,000 ohms per volt become unsuitable.

It would be a mistake, however, to draw the conclusion from Mr. Stein's paper that the high resistance potentiometer no longer has its place in voltage measurements or even that it is inherently less accurate and reliable than the low resistance types. When all the theoretical considerations have been advanced and weighed, the results obtained in actual practical operation over a long period of time remain the deciding factor. In our company we have enjoyed daily experience, excepting Sundays, with both types of potentiometer for something over 20 years. During that time the low resistance potentiometers have given excellent service; they are used with portable galvanometers as though they were indicating instruments. Yet all of them have shown gradual changes in the resistance of the slide wire due to wear from the sliding contact near the ends of the wire, necessitating finally a return to the maker for readjustment. On the other hand, the high resistance potentiometers have never been repaired or returned to the maker, while the initial accuracy has been retained. A check of one of the high resistance potentiometers made 18 years ago showed errors which, in readings involving the use of the first dial, amounted in no case to as much as 0.005 per cent. A recent check of this same potentiometer shows that this accuracy of reading has been maintained and, furthermore, that the resistances of the 1,000-ohm coils and of the 100-ohm coils differ from those of 18 years ago by less than 0.007 per cent. It would appear, therefore, that 1,000-ohm coils may be adjusted with at least the same precision and will remain at least as permanent, as coils of lower resistance.

One of the inherent inaccuracies of the low resistance potentiometer with single dial and slide wire was due to the fact that the standard cell balance was obtained using the part of the potentiometer between the 5th and 15th coils of the main dial, whereas the unknown voltage was measured on the part beginning from the other end of the dial. This objection has been met in the arrangement used in the recent edition of this potentiometer, shown in Fig. 3 of Mr. Stein's paper. Likewise, the current flowing through the potentiometer set for the 0.1 range could not be checked against the standard cell; it was necessary to return to the 1.0 range whenever the current was to be checked. This objection also has been overcome as shown in Fig. 3. In the new arrangement the reliability of readings obtained with the 0.1 and 0.01 ranges depends, of course, upon the maintained accuracy of the shunting resistances and of the additional resistances which must be introduced for the standard cell balance. In this respect, however, the new arrangement is in no way more susceptible to error than other multiple-range potentiometers or its predecessor.

The choice of potentiometer to be used depends on the type of measurements to be made. For rapid measurements in work of an investigational character we find the single dial and slide wire type of potentiometer to be more suitable; the accuracy expected is of the order of 0.05 or 0.02 per cent. For calibration work and for precision measurements the high resistance Feussner type has given excellent service.

It has been found convenient to use dry cells as the source of current for both types of potentiometer. Mr. Stein's curve of Fig. 4 shows the slow rate at which the current changes between the 14th and 30th hours after charging the storage cell which is the source of current, but the early part of the first 14 hours, while gas is still escaping, is not so satisfactory. It has been our experience that an appreciable time must elapse after the cell has been charged before the current steadies down to the point where rechecking of the current needs to be made only at long intervals. Dry cells may be used with the low resistance type of potentiometer where the current required is 0.02 ampere since the effect of changes in room temperature takes place slowly, the discharge curve is practically horizontal for long periods of time, and rechecking of the battery current can be made with rapidity. The battery circuit is opened as soon as use of the potentiometer has been completed, and only a few minutes are required when the circuit again is closed until the current attains a stable value. With the high resistance potentiometer the draft of current is so small that the dry cells are left permanently connected in circuit. In this way it is necessary to recheck current only at intervals of an hour or so, and the cells need to be replaced at intervals of several months. The dry cells represent a saving both in testing time and in battery expense.

Mr. Stein makes frequent reference to an apparent disadvantage in speed of galvanometer operation with the high resistance potentiometer as contrasted with the low resistance type. Reference to the catalog of his company shows that a galvanometer of a satisfactory type, having a period of six seconds, can be obtained with a 10-ohm coil or with a 500-ohm coil. In the case of the former, the published sensitivity is 0.1 microvolt per millimeter measured at the galvanometer terminals, while the recommended external damping resistance is 50 ohms. As he shows in Appendix III, the usual low resistance potentiometer introduces a resistance of only 25 ohms into the galvanometer circuit so that this particular galvanometer would be somewhat overdamped when used with such a potentiometer. On the other hand, the galvanometer with the 500-ohm coil has a recommended external damping resistance of 10,000 ohms; in consequence, the high resistance potentiometer mentioned by Mr. Stein as introducing a resistance of 5,000 ohms in the galvanometer circuit would likewise give the same degree of overdamping. The published volt sensitivity of this galvanometer, however, is 0.25 microvolt measured at the galvanometer terminals. There is no choice therefore between the two methods as to speed of operation and the sensitivity of both galvanometers is adequate where the voltage to be measured is of the order of at least 50,000 microvolts. This agrees with our general experience. As a matter of fact, work is retarded more by having the galvanometer slightly underdamped than when it is appreciably overdamped. A certain amount of time is required to adjust the potentiometer dials to a new setting and with a galvanometer having a period of the order of six seconds no time is lost if the galvanometer is somewhat overdamped.

Mr. Stein's theoretical contentions concerning volt boxes are correct. Practically, however, it is not feasible to use a volt box with as little as 10 ohms per volt for the measurement of voltages of the order of 100 volts, on account of the high power loss with resultant uncertainties of resistances in the volt box. If 20 ohms per volt be permissible then a suitable galvanometer, used with a low resistance potentiometer having a total battery circuit resistance of 100 ohms, is reduced in sensitivity to one-half the value obtained when the volt box is not used. On the other hand, the high resistance type of volt box does not ordinarily have more than 1,000 ohms per volt, so that when a potentiometer is used in which the total battery circuit resistance is 20,000 ohms, the use of the high resistance volt box reduces the galvanometer sensitivity by only one-sixth of the value enjoyed when the potentiometer was used without a volt box. Perhaps a more correct statement of the situation would be, therefore, that a high resistance volt box with consequent avoidance of heat errors can be used with a high resistance potentiometer without the loss in sensitivity that takes place when a volt box is used with a low resistance potentiometer.

There is no question that low resistance potentiometers are essential in modern industry. It is doubtful, however, if they can take the place of the high resistance potentiometer as an instrument of precision. In order to avoid the use of a slide wire which is subject to wear and sometimes to difficulties of operation, the desirable 4 and 5 dials of fixed resistance units must be secured by means of shunt circuits of some sort, often with numerous compensating units. These call for coils of odd values of ohms which can hardly be measured with the precision possible with decimal value coils although the accuracy of the potentiometer is equally dependent upon the adjusted and maintained accuracy of these coils.

The suitability of low resistance potentiometers for the measurement of thermocouple e.m.f. needs little argument. Viewed as a practical consideration, however, it is doubtful if a temperature difference as small as 0.001 cent. should be measured with a single thermocouple and a low resistance potentiometer, when an accurate determination of such a temperature difference with a resistance thermometer can be carried out so much more comfortably.

Marion Eppley: I think Mr. Stein has overestimated the difficulty of making 1,000-ohm coils that are constant to 0.01 per cent and has underestimated the difficulty of making lower valued coils of the same constancy. To illustrate this point, I have known "sealed" one ohm coils, *i. e.*, coils so enclosed as to be protected against humidity changes, action of oil, etc., to vary by more than 0.02 per cent and, on the other hand, instruments which I have checked, having many 1,000-ohm coils, have remained constant to 0.01 per cent, even though the coils were of the ordinary unenclosed type. With resistances higher in value than 1,000 ohms it is a different story.

I have used both high resistance and low resistance potentiometers and the advantages and disadvantages of both types seem to be very evenly balanced.

I am glad that the points having to do with galvanometer damping, and especially that example dealing with the reading of shunts on page 1307, second column, have been made more clear by the author's verbal explanation. It should be stressed constantly that galvanometer characteristics must be suited to the circuit and that a galvanometer giving the desired results with a low resistance network will not do the same in a network of high resistance. However, largely due to Mr. Stein's efforts, galvanometers of individual characteristics suitable to a wide range of circuits are no longer special instruments, but are stock patterns. Whether the circuit be of high resistance or of low resistance, galvanometer damping cannot be ignored. It is only fair to say that galvanometers with high critical damping resistances and adequate sensitivity are apt to have slightly longer periods than those of low critical damping resistance.

One point with reference to galvanometer damping has not been touched upon. This is the difficulty in thermocouple potentiometers of having the galvanometer critically damped when in the low resistance potentiometer circuit proper and also when across the standard cell coil which must be in the nature of things of a much higher resistance than that of the potentiometer circuit proper. Either a shunt on the galvanometer, if it has a critical damping resistance suited to the thermocouple circuit, or series resistance, if the critical damping resistance is suited to the standard cell coil, must be provided for use in one or the other circuit. It is preferable to have the critical damping resistance a little higher than the effective resistance of the potentiometer circuit plus that of the thermocouple, making up the difference with a resistance free from parasitic e.m.fs. Then a shunt on the galvanometer can be used when connected across the standard cell coil without too greatly lowering the galvanometer sensitivity.

On page 1307 at the end of the first paragraph in speaking of the calibration of the slide wire potentiometer, it is said that "If the comparative values of the main resistors are known to 0.01 per cent, the uniformity of the slide wire may be determined with this same precision." It should be noted that the uniformity of the slide wire is checked only at the 13 points given by this set-up. This check cannot tell what is between the points tested. It should be emphasized, however, that in practise slide wires can be made extremely uniform. On the other hand, the dial instrument can be checked at every point.

On page 1305, last paragraph, notice is taken of the "zero drop" in the Feussner potentiometer. This is constant if the switches are properly made. As stated, it is not proportional. In two German instruments of the highest grade which were examined, the zero drop in each instrument had an average value of 0.8 microvolts with wide variations as the switches were shifted off zero and back again. It has been reduced to 0.5 microvolt in certain other instruments with which I am familiar and is practically constant. It is thus less than 0.1 of one stud on the last dial. It would appear from an investigation of this circuit which I have just made that the zero drop can be reduced to approximately 1/3 of 0.5 microvolts. If this is so, it will be possible to reduce the resistance of the circuit to 1,000 ohms per volt for use where such a reduction is advantageous. Such a reduction would cause the zero drop to rise to say 2 microvolts as indicated by Mr. Stein, but still this would cause an error of only 0.2 of one stud on the last dial.

The White potentiometer is made in two ranges—"10,000 microvolts" and "100,000 microvolts." This rating is somewhat ambiguous, for in either case the instrument has only four dials. The precision based upon a full scale reading is the same in either instrument, *i. e.*, 0.1 of the last dial, gained by galvanometer deflection. Stated as it is, it might seem that the 100,000 microvolt instrument would read to six significant places and, therefore, have the greater precision. This is not so. Both instruments cover only five significant places and one starts one place higher and ends one place higher than the other.

N. E. Bonn: It is very gratifying to note that the potentiometer is at present attracting considerable attention in the technical press. Only two months ago Eppley and Gray[2] published a paper describing a new American edition of the Feussner potentiometer.

While the present paper touches upon a large number of topics pertaining to potentiometer design, two features are given especial prominence. One of these is a discussion of the superiority of the low resistance potentiometer over instruments having a high internal resistance; the other is the new modification of the White potentiometer shown in Fig. 6.

The advantages of the low resistance potentiometer in affording greater sensitivity are of real importance only in measuring e.m.fs. of less than 0.1 volt. For higher voltages or in cases where the source has a high internal resistance, these advantages largely disappear, and the choice of an instrument must be based on other and more important considerations.

In the section under "Galvanometer Considerations" a case is cited involving the measurement of 0.3 volt. It is pointed out that a particular low resistance galvanometer, when used in conjunction with a certain low resistance potentiometer, exhibits good sensitivity and damping, but if the *same galvanometer* were used with a high resistance potentiometer the results would not be satisfactory. This statement is unquestionably correct, but is by no means a valid argument against the high resistance potentiometer. No one familiar with the fundamentals of electrical measurements will even attempt to use a galvanometer of such low resistance with a high resistance potentiometer. The argument could easily be reversed by assuming the availability of a suitable high resistance galvanometer, and in such an event greater sensitivity can be obtained with the high resistance potentiometer than would be the case if a low resistance potentiometer were used. As a matter of fact, one does not select a potentiometer to suit a given galvanometer, but vice versa. The cost, period, and convenience of a galvanometer are in no way dependent upon its internal resistance and critical damping. Simple and convenient galvanometers are available that are admirably suited to high resistance circuits.

In calculating the maximum errors that may arise from the manipulation of dial switches, Mr. Stein makes the assumption that compensation will always remain accurate to 0.01 per cent. In other words, a nine-ohm coil initially adjusted to equality with a group of nine one-ohm coils may be relied upon to maintain that equality to within 0.01 per cent over extended periods of time. Such an assumption does not appear to be warranted in the light of every day experience. Even granting Mr. Stein's own contention that low resistance coils can maintain their adjustment to ± 0.01 per cent, it may well happen that the changes in the coils will be of opposite sign, particularly since the nine-ohm coil must be geometrically different from the one-ohm coils. Under such conditions the maximum error from compensation must be assumed to be 0.02 per cent. If this is done, the total error from dial manipulation exceeds one step of the fifth dial for the higher range, Mr. Stein's statement to the contrary notwithstanding.

Another important consideration is the question of zero shift. In discussing the Feussner potentiometer, Mr. Stein duly points out that this instrument has an inherent false zero, yet he fails to mention the fact that the same is true of his favorite arrangement of Fig. 6. When all dials are set on zero, there are present in this circuit two presumably equal and opposite electromotive forces. One of these is due to coil Z of the upper potentiometer carrying a current of 0.01 ampere; the other is present in the coils of the lower potentiometer carrying a current of 0.001 ampere. Now assume that the resistance of coil Z will have increased to the extent of only 0.01 per cent in the course of time and that the resistance of the lower potentiometer coils will at the same time have decreased by the same relative amount. Since each of the two opposing e.m.fs. amounts to 2467.5 microvolts, the zero shift from this source alone may amount to 0.5 microvolts, and this equals five full steps on the last dial for the low range. The situation is still further aggravated if one takes into consideration that the standard cell coils of the two potentiometers may also change in opposite directions, one being of the order of 100 ohms, while the other has a value exceeding 1,000 ohms. In such an eventuality (and this is entirely within the realm of probability) the zero shift error may well exceed one full step of the fourth dial (dial V) of the low range.

In view of such relatively large possible errors, there would appear no justification for the use of two batteries and six dial switches. Better results may be obtained with a single battery and five dial switches, particularly with the Wenner circuit shown in Fig. 6.

Marion Eppley: Dr. Brooks has described his potentiometer in detail and I am of the opinion that when this is made available it will mark a great stride forward not only in the accuracy of measuring electromotive forces, but also in ease and speed.

I am heartily in accord with the method of maintaining unsaturated cells mentioned by Dr. Brooks.

Bubbles, if they form, can be removed not only by heating the amalgam side as described by Dr. Brooks, but also by tapping the amalgam limb. This is so much a knack that I hesitate to try to describe it. Cells treated by either method are quite uninjured, but should be given a period of rest.

I. Melville Stein: Referring to Dr. Robinson's comments, the value of parasitic e.m.f. given for dial switches is intended to be a safe maximum value, as are also the values given for well-designed slidewire contacts. Usually the parasitic e.m.fs. will be lower, but probably it is not safe to assume lower values. In this connection, it should be borne in mind that usually there is only a single slidewire contact in the circuit, whereas the usual number of switch contacts varies from five to ten or more. I agree fully with Dr. Robinson's comments referring to high- and low-resistance potentiometers. However, I cannot agree with his comments pertaining to galvanometer requirements. This will be clear from my later remarks in answer to other discussions of the paper.

I agree fully with Dr. Robinson that the well appreciated advantages of the 20,000-ohm potentiometer can be realized in dial type potentiometers of much lower resistance, but in designing for lower resistance, numerous precautions must be taken, as I have tried to indicate in the paper.

Referring to Dr. Brooks' discussion, I should like to add the following comments: While it is true that relative stability is the most important point in the resistance coils of a potentiometer, this consideration does not help the situation appreciably if the design requires coils of widely different values, some of them being as high as 1,000 or 10,000 ohms. This is particularly important when the effect of atmospheric humidity on relatively high resistance coils of substantially different values is considered.

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[2] Review of Sci. Inst., New Series, Vol. 2, No. 4.

In referring to the use of a false zero setting of the galvanometer, I did not intend to place emphasis on any particular means for obtaining a false zero. I quite agree with Dr. Brooks that electrical means for establishing the false zero are frequently more convenient than mechanical means.

Referring to Mr. Thompson's remarks, I had no intention of indicating that a high-resistance potentiometer is useless. What I attempted to point out is that the high-resistance potentiometer is always susceptible to more sources of error than a well-designed low-resistance potentiometer, and, for certain classes of measurements, the high-resistance potentiometer cannot be used at all. On the other hand, the low-resistance potentiometer is equally as good or better for making measurements of the class that can be made with a high-resistance potentiometer.

I believe that Mr. Thompson has entirely misunderstood some of my statements referring to low-resistance potentiometers. He seems to have assumed that all low-resistance potentiometers are of the slidewire type, and this is distinctly not the case, as will be seen from the illustrations and statements in the paper. However, his remarks bearing on the relative performance of high-resistance potentiometers and low-resistance potentiometers of the slidewire type deserve some comment. He makes it clear that the changes he has observed in slidewire potentiometers are due to wear on the slidewire. In a properly designed slidewire potentiometer, such wear occurs only when the instructions to clean and lubricate the slidewire, occasionally, are not followed. Repeated tests, involving as many as 500,000 movements of the contact along the slidewire, show that, within the accuracy of reading the slidewire setting, there is no change of resistance of the slidewire if the wire is reasonably clean and lubricated. Mr. Thompson's remarks referring to the constancy of high-resistance potentiometers are not clear for several reasons. No information is given pertaining to the atmospheric humidity at the time the measurements were made. Also no information is given as to the number of years that the coils had aged before the first measurements were made; in other words, the stability during the first two or three years after the potentiometer has been built is at least as important as the stability from, say, the 3rd to the 21st year.

Mr. Thompson refers to an inherent inaccuracy in a particular form of low-resistance potentiometer, due to the point on the potentiometer resistance at which the standard cell connection is made. He then states that the inaccuracy has been eliminated in a more recent design of the same instrument. Obviously, therefore, if there were any error due to this cause, it certainly would not be an inherent one. This improvement in the later design is theoretical rather than real because all of the potentiometer coils are low in value and are identical in construction.

Referring to Mr. Thompson's comments on the constancy of potentiometer batteries, it is well known that a storage battery should not be used for precise measurements with a potentiometer immediately after the battery is taken off charge. If, however, the user takes the battery off charge and connects it to the potentiometer when he leaves the laboratory, say, at 6 o'clock in the evening, the first 14 hours of discharge will have occurred by 8 o'clock in the morning when he returns to the laboratory. A 60-ampere-hour storage cell, which can be purchased for about $6.00, when used with a potentiometer drawing 0.02 ampere, will require charging only once every two or three weeks to keep it in good condition for the most precise work with a potentiometer.

Referring to Mr. Thompson's remarks on galvanometers, there is no difficulty at all in obtaining a very satisfactory galvanometer for use with a high-resistance potentiometer in making measurements at relatively high values of e.m.f. On the other hand, when it is necessary to measure very low values of e.m.f., there are no galvanometers of any make or type available that would permit the use of a high-resistance potentiometer. It is in the intermediate range of e.m.f. where the high-resistance potentiometer may still be used, but is handicapped by lack of sensitivity, that its use involves working with a galvanometer having characteristics poorer than those of a galvanometer that could be used with a low-resistance potentiometer for making the same measurements. To make clear the difficulties involved in proper damping of the galvanometer when working with a high-resistance potentiometer, it is necessary only to consider specifically the performance of the galvanometer which Mr. Thompson has mentioned as being satisfactory for use with the high-resistance potentiometer. It is logical to assume that this galvanometer has sufficient sensitivity for the measurements that are to be made with the high-resistance potentiometer and that it has this sensitivity with its proper external damping resistance in series. As Mr. Thompson has indicated, the proper external damping resistance is 10,000 ohms. With the high-resistance potentiometer, 5,000 of this 10,000 ohms is in the potentiometer, and by manipulation of the potentiometer dials, may be reduced to almost zero, thus producing a very large change in the effective damping resistance. If a low-resistance potentiometer were used, the 10,000-ohm damping resistance could be a 10,000-ohm fixed resistance coil in series with the galvanometer and the damping resistance would be altered by not more than 12.5 ohms in 10,000 due to manipulation of the potentiometer; in other words, when working with the high-resistance potentiometer, the damping resistance may vary as much as 5,000 ohms in 10,000, whereas when working with the low-resistance potentiometer, the damping resistance will not vary any more than 12.5 ohms in 10,000. It should be obvious from these figures that the damping problem, when working with the low-resistance potentiometer, is very much simplified; in this particular instance, practically eliminated.

I do not believe that Mr. Thompson will find many who will agree with him that it is better to work with a galvanometer slightly overdamped rather than slightly underdamped. It has been my own experience, and the experience of all those with whom I have discussed the matter, that it is more convenient to work with a galvanometer slightly underdamped.

Referring to volt boxes, I agree with Mr. Thompson that it is not practical to use a very low resistance in the volt box, and I indicated in the paper that it was desirable to make the total resistance of the volt box several hundred ohms per volt. The point which I attempted to make, and which, apparently, Mr. Thompson has misunderstood, is that *for the same sensitivity*, when working with a low-resistance potentiometer, it is possible to use *higher* resistance in the volt box than may be used when working with a high-resistance potentiometer. Mr. Thompson's argument in connection with the reduction in sensitivity caused by the insertion of the volt box is equivalent to saying that if the sensitivity is already very poor because of the high resistance in the potentiometer, it cannot be made much worse because of the resistance added by the volt box.

Referring to Mr. Thompson's comments on the relative accuracies of high- and low-resistance potentiometers, I think it best to refer to Appendix II, which gives concrete values for the errors to be expected in low-resistance potentiometers of good design. As to the relative merits of resistance thermometers and thermocouples for measuring temperature, it is impossible to construct a satisfactory resistance thermometer which would be small enough to make some of the temperature measurements which can be made with single junction thermocouples.

Referring to Dr. Eppley's remarks, I should say first that the statements in the paper pertaining to the relative stability of high-resistance and low-resistance coils are not estimates, as Dr. Eppley has indicated, but are based on actual observations on over 1,000 coils measured in connection with research work on the stability of resistance coils and on careful measurements on many thousands of resistance coils in regular production. However, to further support the statement made, I quote below from Circular No. 21 of the Bureau of Standards:

> A few words may be said regarding the relative advantages of high- and low-resistance potentiometers. The chief advantage of the low resistance is in sensitivity, which increases as the resistance is reduced. In the low resistance instrument, the effect of poor insulation and possible leakage between parts is less important than in the case of high resistance. The change of the resistances with time and their variation with atmospheric humidity are also less in the case of low resistances.

I must disclaim most of the credit which Dr. Eppley very generously accords me in connection with galvanometer design. If any credit is due, it should go to the organization, of which I am but a small part.

Referring to Mr. Bonn's comments, I agree with him that in measurements that do not require high sensitivity, the high-resistance potentiometer may be used, but at some sacrifice in accuracy, as I have already indicated.

In commenting on the part of the paper having to do with "Galvanometer Considerations," Mr. Bonn bases his remarks upon a misinterpretation of what is stated in the paper. He apparently has confined his attention to certain introductory remarks, and has ignored the main point, which is that, even if the particular form of galvanometer were rewound to better adapt it to working in a high-resistance circuit and provided proper damping were taken into consideration, the required sensitivity would be impossible to obtain. Mr. Bonn's remarks relative to reversing the argument, by assuming the availability of a suitable high-resistance galvanometer, are clearly inaccurate. If the galvanometer has sufficient sensitivity for use with a high-resistance potentiometer, it will necessarily have sufficient sensitivity for use with a low-resistance potentiometer, and, in addition, the damping characteristics will be superior when used with the low-resistance potentiometer, as has been indicated above in responding to Mr. Thompson's discussion. Mr. Bonn is also in error in stating that one does not select a potentiometer to suit a given galvanometer, but rather does the reverse. It is true that in many cases where the designs of potentiometers and galvanometers have been carefully worked out for a particular purpose and the conditions are such as to permit some latitude in the choice of the galvanometer, the user may select the potentiometer first and the galvanometer afterward. However, in measurements that require either very high sensitivity or very high speed in making measurements, first attention must be given to the availability of a suitable galvanometer, and having available the proper galvanometer, a potentiometer must be chosen so as to retain, not destroy, the essential characteristics of the galvanometer. This point has been emphasized by Dr. Brooks in his discussion of the paper. I must disagree also with Mr. Bonn's further comments relative to cost, period, and convenience of galvanometers. Space is not available to make a complete answer, but most of what I should want to say in response to these comments will be found in the paper and in the discussion above.

Referring to the potentiometer shown in Fig. 6 of the paper, the assumptions which Mr. Bonn makes in discussing the error resulting from inaccuracy in the compensating coils are his own and do not agree with the statement in the paper which is as follows: "The final assumption is that the compensating coils k are adjusted to cause no error greater than 0.01 per cent in dials I and II and no error greater than 0.1 per cent in dials III and IV." This assumption, as stated in the paper, is justified by the low value of the coils in question, combined with proper design for use in a very precise potentiometer. Every day experience, even if correctly interpreted, can hardly be taken as a guide in considering the performance of an instrument designed especially for extremely precise work, as few can claim every day experience with instruments of that character. There is no justification for doubling the error indicated in the paper, as Mr. Bonn has attempted to do.

The false zero, even if it existed in the potentiometer shown in Fig. 6 of the paper, would not be an inherent one, as Mr. Bonn has indicated. The assumptions which Mr. Bonn makes relative to resistance changes, which would cause a false zero, are unwarranted, but, even if they were proper assumptions, his conclusions would still be wrong. As I have indicated in the paper and as Dr. Brooks has clearly brought out in the discussion, when using a potentiometer to make precise measurements of very low values of e.m.f., it is usually necessary to work with a false zero in order to compensate for parasitic e.m.fs. in the circuit. The false zero adjustment would take care of any error resulting from minute changes in the resistance of the coils in question. It would be ridiculous to assume that the resistance coil errors were less stable than the parasitic e.m.f. in the circuit, resulting from extraneous causes. In any precise low-voltage potentiometer, the stability of the standard cell coils needs unusual attention. In the potentiometer circuit shown in Fig. 6 of the paper, the standard cell coil in the "upper" potentiometer needs to be more stable than the one in the "lower" potentiometer because relatively low accuracy is required in the "lower" potentiometer circuit. Accordingly, it is appropriate to use a higher value for the standard cell resistance coil in the "lower" potentiometer circuit. However, should any question arise about the stability of either standard cell coil, it would be a simple matter, because only two coils are involved, to make these coils of the sealed type as developed at the Bureau of Standards.

I must disclaim any favoritism toward the potentiometer circuit shown in Fig. 6 of the paper. It was described in more detail than the others because it had not been described before. The Wenner circuit, which has not been described before, is to be described in detail in a separate paper which is to be published at an early date. This was stated in the paper.

Determination of Synchronous Machine Constants by Test

Reactances, Resistances, and Time Constants

BY SHERWIN H. WRIGHT*
Associate, A. I. E. E.

Synopsis.—In recent years there have been many advancements made in the art of analysis of three-phase synchronous machine operation. Most treatments to date have very properly stressed the theoretical point of view, the practical point of view receiving less attention due in part to the complications involved, particularly those due to saturation effects. In this paper the practical standpoint is stressed and discussed on the basis of observations made from many tests; an important feature of these tests is that saturation effects under short circuit were studied by applying short circuits to machines operating at rated voltage.

Due to serious saturation effects, the so-called constants of synchronous machines may have different values under different conditions. What are considered to be the most important of these values are discussed, and by defining certain saturated and other values, an attempt is made to provide a definite basis for the specification of machine constants.

Part I reviews certain basic concepts and discusses practical considerations of test methods. Part II describes methods of determining the more important constants by test. Part III illustrates the application of these methods to actual power machinery, and presents tabulated test results as well as a table of typical constants. The Appendixes are devoted to certain additional tests and conclusions, and to development of formulas.

* * * * *

INTRODUCTION

THE importance of the analysis of synchronous machine operation is well evidenced by the considerable literature on this subject, representing definite steps in the advancement of the art. Briefly, the major steps in this advancement are as follows: The two-reaction theory was introduced by A. Blondel,[1] and the method of symmetrical components by C. L. Fortescue.[2] An extension of Blondel's two-reaction theory for transient conditions was recognized and adopted by C. F. Wagner and R. D. Evans,[3] for stability studies; this has been developed and amplified by R. E. Doherty and C. A. Nickle and their associates.[4,5]

The novelty of the method of analysis of synchronous machine operation under various conditions lies in the fact that the machine is characterized by a considerable number of constants—reactances, time constants, and resistances. At present there is no accepted set of definitions† which standardize the meanings of these constants. It is the purpose of this paper to discuss three-phase synchronous machine constants from the practical standpoint, to describe methods for their determination from tests, and to describe the application of these methods in the form of extensive tests made on those types of machines found in a power system. The calculation of machine constants by design formulas is treated in a companion paper by L. A. Kilgore.[6]

A major step in the development of machine theory has been the recognition and analysis of the effects of additional rotor circuits such as damper bars (amortisseurs), solid iron paths, etc. Certain machines are characterized by certain additional rotor circuits; further, the more important synchronous machines are those found in three-phase power systems. Accordingly, the machines discussed are those three-phase synchronous machines falling under the following convenient classification.

1. Turbine generators
   This refers to the common non-salient pole turbine generator with solid-iron rotor.
2. Salient-pole machines with dampers
   This refers to the various salient-pole machines equipped with damper windings (amortisseurs, etc., or their equivalent) and includes synchronous condensers and motors.
3. Salient-pole machines without dampers
   This refers to salient-pole laminated-rotor machines which have no rotor circuits other than the field winding. If a machine of this general type has additional rotor circuits such as short-circuiting pole collars, rivets, etc., it should be classified either under (2) or (3) according as the effect of these circuits is significant or insignificant.

Part I of this paper discusses practical considerations involved, and reviews certain basic concepts. Part II describes test methods by which machine constants may be determined. Part III illustrates the application of these methods to actual power machinery—such

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*Central Station Engineer, Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

1. For numbered references, see Bibliography.

†A subcommittee on "Definitions of Terms used in Stability Studies," under the chairmanship of Prof. G. Dahl, has in preparation a report which gives definitions as well as descriptions of test methods of synchronous machine constants. Because of space limitations, precise definitions are omitted here; however, Prof. Dahl's committee report will be presented at the Winter Convention, N. Y., January 25-29, 1932.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

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as turbine generators, synchronous condensers, etc.

I—Fundamental Concepts and Practical Considerations

Phase Sequence Currents in a Three-Phase Synchronous Machine

The analysis of synchronous machines operating under balanced and unbalanced conditions may be considered as based on two fundamentals, the method of symmetrical components, and Blondel's two-reaction theory.

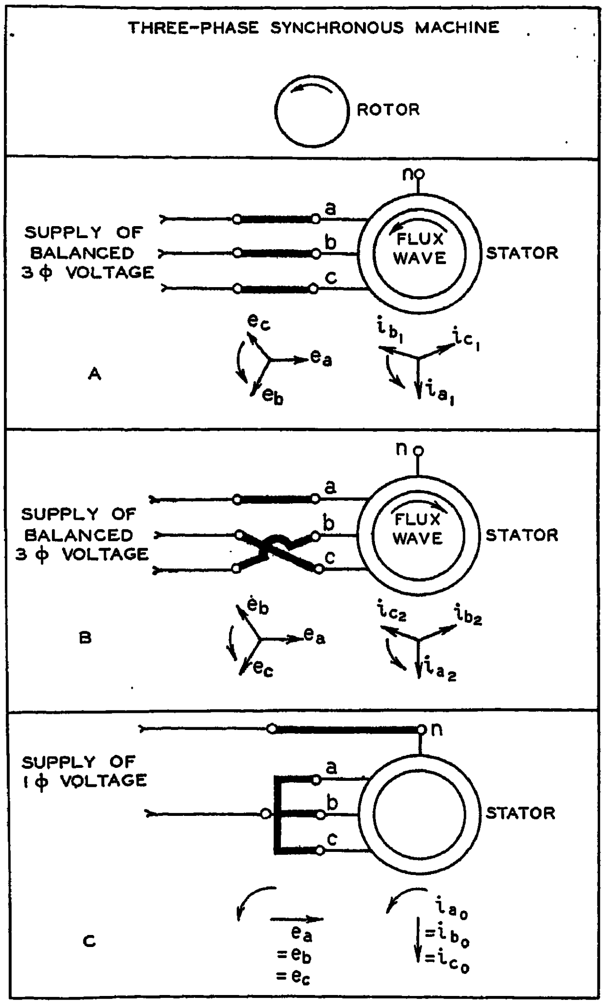

Fig. 1

A—Positive-Sequence Current

B—Negative-Sequence Current

C—Zero-Sequence Current

The application of the three sequence currents (rated-frequency) to a wye-connected machine is illustrated in Fig. 1. The set of three equal stator currents producing a flux wave which rotates at synchronous speed *with* the rotor is thereby identified as positive phase sequence (or simply positive sequence), designated I_{a1}, I_{b1}, and I_{c1} in Fig. 1A; the subscript (1) implies, conventionally, positive sequence. That set producing a flux wave rotating at synchronous speed in a direction opposite to that of the rotor is thereby identified as negative-sequence current, designated I_{a2}, I_{c2}, and I_{b2} in Fig. 1B, the subscript (2) implying negative sequence. Zero-sequence current produces no net fundamental air-gap flux because the three currents are in time phase and the three phases are spaced 120 elec. deg. apart; being in time phase (and equal) identifies them as zero-sequence currents, designated I_{a0}, I_{b0}, and I_{c0}, in Fig. 1C. Positive-, negative-, and zero-sequence currents may exist not only as fundamental-frequency currents as above, but also as harmonics; for example, under balanced conditions all triple-harmonic currents are zero sequence. Unless otherwise qualified in this paper, rated frequency quantities are implied.

Positive- and negative-sequence currents may, as far as their effect on the rotor is concerned, be replaced by a set of permanent magnets concentric with the rotor, alternately north and south poles, and equal in number to the rotor poles. The equivalent effect on the rotor of negative-sequence current is obtained by rotating the magnets at synchronous speed against the rotor direction. The equivalent effect of positive-sequence current is obtained by rotating the magnets at synchronous speed *with* the rotor; the equivalent of a *change in magnitude* of positive-sequence current is to move the magnets radially toward or away from the rotor, keeping their angular velocity constant.

Blondel's two-reaction theory deals mainly with positive-sequence current. The flux wave produced by positive-sequence current is stationary with respect to the rotor, and if the relative position of flux wave and rotor is such that a maximum amount of this flux links the field winding, tending to magnetize or demagnetize the rotor in the axis of the field poles, then that current is a direct-axis current and is affected by a direct-axis (positive-sequence) reactance. Positive-sequence current which tends to magnetize or demagnetize the rotor in the interpolar axis, so there are no net flux interlinkages with the field winding, is a quadrature axis current and is affected by a quadrature-axis (positive-sequence) reactance.

Another classification of positive-sequence currents, important for transient conditions, is according to whether armature current is suddenly or continuously applied. Neglect saturation for the moment and consider the three-phase short circuit from no load of a salient-pole machine whose only rotor circuit is the field winding. In terms of the equivalent magnets, the short circuit is equivalent to suddenly moving the magnets radially toward the rotor; this induces direct current in the field. This phenomenon may be explained in terms of the theorem of constant flux interlinkages.[17,7,8,9] If the total field current were known, the actual armature current could be calculated as the ratio of (the no-load voltage corresponding to that field current), to (synchronous reactance). It is more convenient to account for the increase in rotor excitation by a fictitious reactance such that the short-circuit current is the voltage previous to short circuit (at no load) divided by this fictitious reactance. For a machine whose only rotor circuit is the field winding, this is the transient reactance;[5] the presence of dampers causes greater short-circuit current, and the fictitious reactance is called the subtransient reactance, while transient reactance retains the same significance as before—*i. e.*, it may be considered as that reactance which *would* determine the current if the only rotor circuit were the field winding.

MACHINE CONSTANTS AS AFFECTED BY SATURATION AND OTHER PRACTICAL CONSIDERATIONS

Of the factors affecting machine constants, saturation is one whose effect is quite serious and which must be accounted for definitely. For example, the subtransient reactance of a turbine generator may be 14.5 per cent for a dead short circuit (no external impedance) and 16.5 per cent when external impedance causes lower current and less saturation. Saturation effects are different for different constants and types of machines. In other words, machine constants are not truly constant. It is obviously impractical to use a different value of a constant for each condition of operation. However, there is one value of each constant which appears to be generally more important than any other. Accordingly, it is advocated that in general, only one value of each constant should be specified, and that only when absolutely necessary should two values be used, *both for operation at rated voltage*, but one for *high current or saturated conditions*, and the other for rated current conditions. For example, *unless otherwise qualified, the values of direct-axis transient and subtransient reactances and short-circuit time constants will be understood as those values effective for a dead three-phase short circuit, from rated voltage at no load*, these being termed *saturated values*, for convenience.* Unless otherwise qualified, the value of *negative-sequence reactance will be understood as that value effective when negative-sequence fundamental current is circulated, the magnitude of the current being that of the negative-sequence current obtaining in a line-to-line short circuit from rated voltage at no load, this being termed the "saturated" value.* The values of negative-sequence reactance and direct-axis transient and subtransient reactances and short-circuit time constants which are effective at rated current are termed "rated current" values but may be considered generally of secondary importance. Since saturation effects for zero-sequence currents in the range usually encountered are not large, it is sufficient to state that *zero-sequence reactance will be understood as that value effective when zero-sequence fundamental current equal to rated current is circulated,* this being termed the rated current value. Unless otherwise qualified, values of *direct and quadrature axis synchronous reactances will be understood as the unsaturated values,* since these have been defined and used for many years; when qualified as saturated values, they will be understood as those effective at rated load. The views expressed above should be interpreted as definite recommendations as to what value of each constant should ordinarily be specified.

Machine constants are based on fundamental frequency components, and the sequence reactances (positive, negative, and zero sequence) are the ratios of fundamental reactive components of voltage to corresponding *circulated* fundamental currents, (as advocated by Park and Robertson).[5] Harmonics may exist in current and voltage waves, particularly under unbalanced conditions. It is impractical, in testing, to segregate fundamentals from harmonics; fortunately, however, voltages and currents associated with machines found in power systems are such that r. m. s. values of the total waves and of the fundamental components may usually be taken equal, with small error. To illustrate this point, suppose a voltage or current being measured is made up of a fundamental and a third harmonic of 20 per cent the fundamental; now machine constants are based on fundamental components, and if the peak value of the wave were used in computing, say, a certain sequence reactance, the error might be 20 per cent; on the other hand, the r. m. s. value of the fundamental and the total wave are respectively $1/\sqrt{2}$ and $(1/\sqrt{2})\ \sqrt{(1.00)^2 + (0.20)^2} = (1/\sqrt{2})\ 1.0198$, hence if the r. m. s. value of the total wave is taken as that of the fundamental component, the error is 0.0198 (per unit) or less than 2 per cent.

Resistance is a most important factor concerning time constants of machines. With the armature short-circuited it is usually assumed that the time constant of the field circuit depends on the resistance of the field but not of the armature; similarly, it is usually assumed that the time constant of the armature depends on the resistance of the armature but not of the field. Concerning the impedances to sequence currents, however, resistances are usually unimportant, with the one exception of negative-sequence resistance which may be important due to the rotor loss associated with it. In tests with indicating instrument measurements, a wattmeter measurement, in addition to that of voltage and current, will suffice to determine the importance of the resistance component of any sequence impedance. For simplicity, when an impedance is mainly reactance, no discrimination will be made between numerical values of impedance and reactance. For definiteness it is assumed that the resistances of field and armature circuits are the 75 deg. cent. values.

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*In the case of quadrature-axis constants, the corresponding saturated values may, in order to make their test determination as practical as possible, be defined as those values effective when a machine is short-circuited from the slip test (described later) while carrying quadrature-axis current equal to rated current.

Fundamental Basis for Transient Condition Analysis

In transient condition analysis, voltage and current are conveniently divided into certain definite parts. For armature current, the first distinction to be made is that between symmetrical and asymmetrical components. The classification for armature voltage is the same as that for the symmetrical component of armature current; this classification gives:

1. A sustained component.
2. A slowly-decaying (or changing) component.
3. A rapidly-decaying (or changing) component.

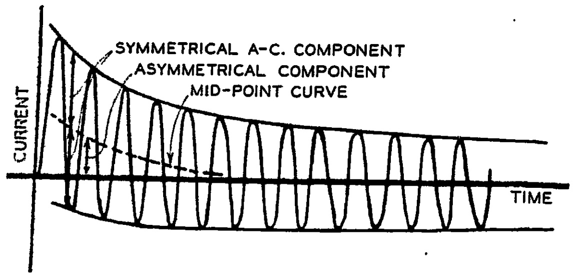

Fig. 2—Typical Wave of Short-Circuit Current

In certain cases, some components are zero; for instance, if a short circuit occurs at such an instant that the current wave is symmetrical, the asymmetrical component is zero.

Consider the current wave in Fig. 2. The symmetrical component is alternating current and is readily determined by drawing two envelopes; half the distance between envelopes, at any instant, is the symmetrical component (envelope value). The asymmetrical component, often called the d-c. component, is determined by drawing a mid-point curve; the distance from the latter to the line of zero current at any instant is the asymmetrical component. This component is in many cases mainly direct current, but may include a large second harmonic as in the case of a three-phase short circuit of a salient-pole machine without dampers; in such a case the second harmonic has positive peak values at the same instants that the symmetrical alternating current has positive and negative peak values, hence the mid-point curve becomes a curve tangent to the total asymmetrical component as in Fig. 3.

Units

In general, it seems unnecessary to use only per unit or only percentage values, one to the exclusion of the other. In analytical work it is often a distinct advantage to use per unit values. In this paper per unit values are generally employed. In calculations of reactances from tests the possibility of error is minimized if the ohmic value is first computed, and this divided by normal ohms;[5] normal ohms, for a given kva. and voltage base, is simply the number of ohms corresponding to 1.00 per unit (or 100 per cent) impedance and is equal to rated line-to-neutral voltage divided by rated line current.

II—Description of Test Methods

Direct-Axis Reactances

Synchronous Reactance X_d. The standard A. I. E. E. definition is, in effect, as follows: Synchronous impedance is the ratio of (field current required to circulate rated current on sustained three-phase short circuit) to (the field current which *would* produce rated voltage at no load if there were no saturation); referring to Fig. 4A, $X_d = a/b$. Another way of defining X_d, one which the author has found results in a clearer conception of the meaning of X_d, is: With a sustained three-phase short circuit, and the field current at any arbitrary value, X_d is (the air-gap line voltage corresponding to this field current) divided by (the sustained short-circuit current). Thus, from Fig. 4B, $X_d = c/d$. The methods in Figs. 4A and 4B give the same result from the same data, giving the unsaturated value.

The slip test[5] affords an alternative means of determining X_d. With the field open, balanced three-phase voltage of about ¼ rated value and rated frequency is applied; either the frequency of applied voltage or the rotor speed is adjusted to give a low value of slip—as evidenced by a very low frequency voltage across the field. Fig. 5 shows the general character of an oscillogram for this test. The slip must be lower than indicated, lest induced rotor currents make X_d appear lower than it really is. When the rotor is magnetized in the direct axis, the generated field voltage is zero, and the ratio of applied voltage to current is X_d.

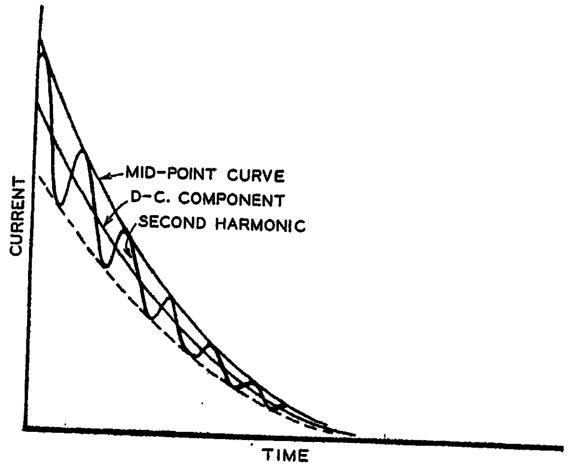

Fig. 3—Asymmetrical Component of Current for a Salient-Pole Machine without Dampers

Transient and Subtransient Reactances X_d' *and* X_d'' *(Saturated Values) Determined from Analysis of a Dead Three-Phase Short Circuit from Rated Voltage at No Load.* The procedure, with pertinent details, will be given for the determination of X_d' and X_d'' of any three-phase synchronous machine, by analysis of an oscillogram of a dead three-phase short circuit from rated voltage at no load.* The machine is driven as a generator, at no load and rated voltage, and suddenly short-circuited. The analysis of the oscillogram reproduced in Fig. 6 will be described. Two envelopes and the mid-point curve are drawn for the wave of each phase. Two factors are computed for each wave, one for the asymmetrical and one for the symmetrical component.

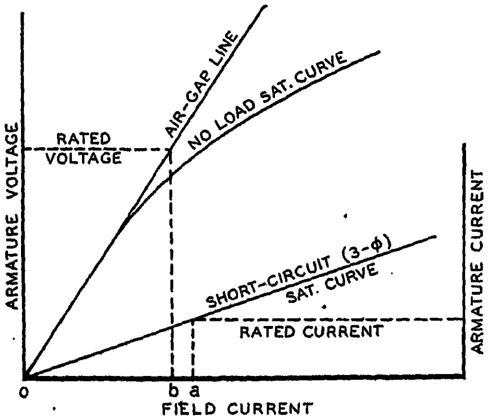

Fig. 4a—Synchronous Reactance $X_d = a/b$ (A. I. E. E. Def.)

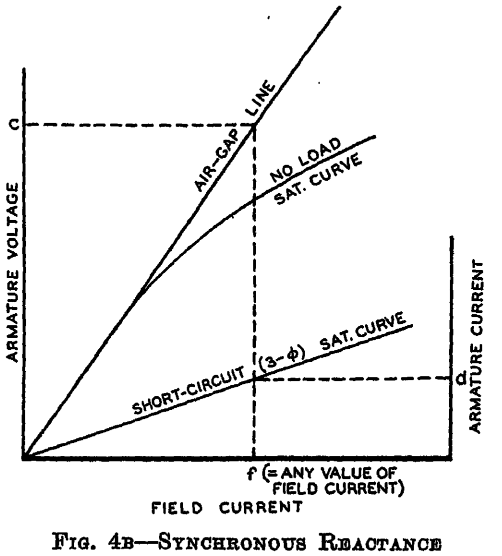

Fig. 4b—Synchronous Reactance $X_d = c/d$

Note: If c and d are in volts and amperes, and not per unit values, then c must be line-to-neutral voltage

The factor for the asymmetrical component, times the distance from the mid-point curve to the zero-current line, at any instant, converts this distance to per unit current; it equals (amperes per unit distance of deflection) ÷ (rated r. m. s. current). The factor for the symmetrical component, times the distance between envelopes (usually more conveniently measured than half the distance) converts this distance to per unit r. m. s. current; it equals $1/(2\sqrt{2})$ or 0.354 times the asymmetrical component factor. The asymmetrical components (per unit values) are plotted on semi-log paper (one scale logarithmic, one uniform) as in Fig. 7a;

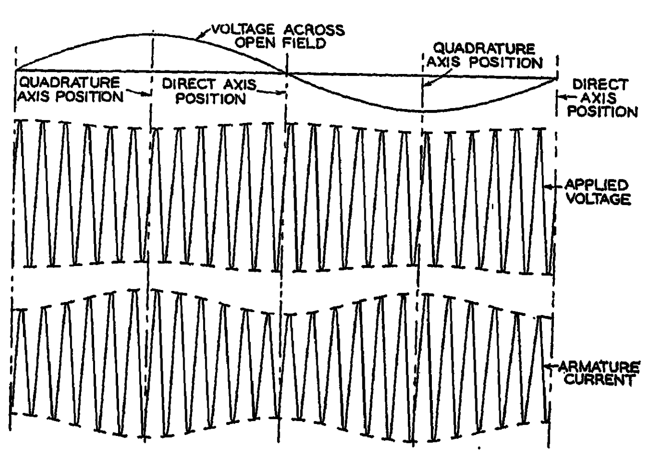

Fig. 5—"Slip" Test for X_d and X_q

In practise the slip should be much less than indicated above. If per unit system is not used, voltage must be line-to-neutral value in formulas below

$$X_d = \frac{\text{Applied voltage}}{\text{Line current}} \text{ for direct-axis position}$$

X_q = same for quadrature-axis position

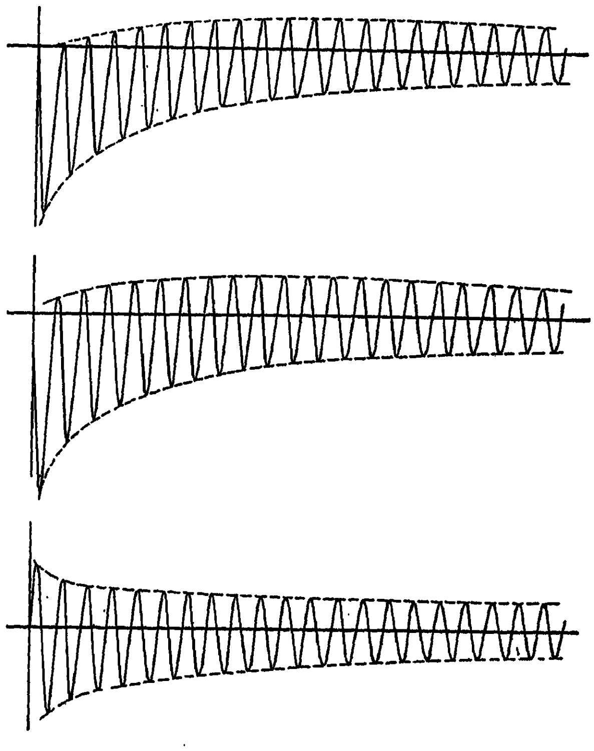

Fig. 6—Typical Waves for Three-Phase Short Circuit

extrapolation, as shown by dotted lines, gives initial values of the asymmetrical component in each phase. The value of this component in any phase depends upon the particular instant of short circuit. The maximum possible value is obtained by the graphical method in

---

*If T_d' is determined from this test (it easily can be), there should be no appreciable external impedance in the field circuit, such as field resistors, etc. The ideal condition would be to supply field current directly from an "infinite d-c. bus."

Fig. 7B; *a*, *b*, and *c* are laid off (uniform scale) along three lines 60 deg. apart, the largest value along the middle line; perpendiculars are drawn to each line, through *a*, *b*, and *c* and the point where these three perpendiculars meet determines point *M*. Then the maximum possible asymmetrical component has an initial value *O M*. This method applies to all machines having short-circuit current whose symmetrical component is a sine wave.

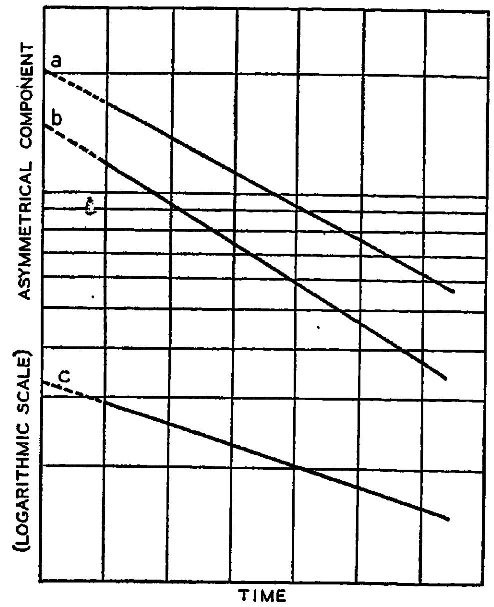

Fig. 7A—Semi-Log Plot of Asymmetrical Components of Waves in Fig. 6

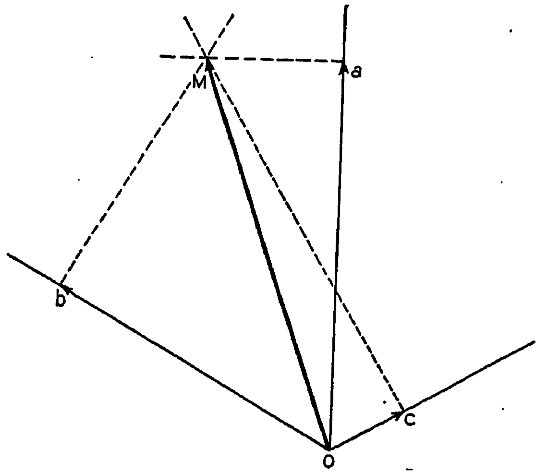

Fig. 7B—Determination of the Maximum Possible Instantaneous Value (*O M*) of the Asymmetrical Component, from the Actual Instantaneous Values in Fig. 7A

The average of the per unit r. m. s. values of the symmetrical components is plotted in Fig. 8. (Errors are minimized by taking this average.) Since both envelopes cannot be drawn before one-half cycle after the short circuit, there is no measured average before this time. Subtransient reactance depends on the initial (zero time) current hence the latter must be determined accurately. Most machines have, on three-phase short circuit, a wave of symmetrical current which can be taken as sinusoidal, hence the initial current $I'' = 0.707$ times the initial value of the maximum possible asymmetrical component *O M*. X_d'' is then the ratio of voltage before short circuit (rated voltage, hence = 1.0) to I''. See Fig. 8. The point determined by I'' may now be joined to the curve by a (dotted) smooth curve.

X_d' is the ratio of voltage to current, the latter being the initial symmetrical value neglecting the initial rapidly decaying portion. That is, in Fig. 9A, the difference $\Delta i'$ is replotted on semi-log paper in Fig. 9B; extrapolation gives $(\Delta i')_0$, which is then replotted in Fig. 9A. The initial *transient* current $I' = (\Delta i')_0 +$ sustained current I, and X_d' is computed as the voltage before short circuit $\div I'$.

Subtransient Reactance X_d'' from Locked Line-to-Line Test. This affords an alternative method for measuring X_d''. See Fig. 10. This is not practicable for determining the saturated value for turbine generators; for salient-pole machines with dampers, however, the value measured at rated current is very nearly the saturated value of X_d''.

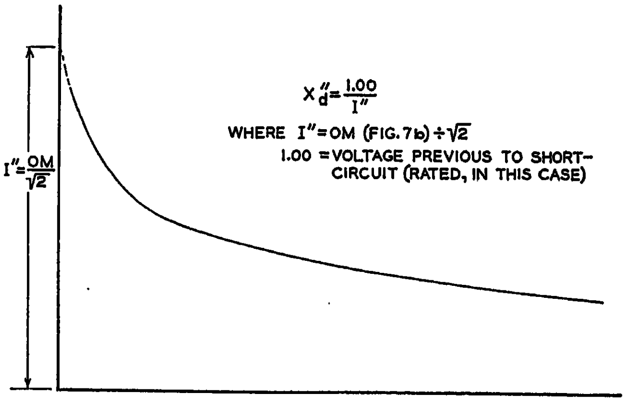

Fig. 8—Determination of Subtransient Reactance from Three-Phase Short Circuit at Rated Voltage No Load

For either wye or delta machines, single-phase voltage is applied between any two line leads, with the field winding short-circuited on itself and the rotor at standstill. With about ¼ rated current circulating (rotor heating should be watched, with turbine generators), readings of voltage and field current are taken for various rotor positions, over a pole pitch. Two rotor positions are determined, one for a maximum value of the ratio of field current to applied voltage, called the direct-axis position, and the other for a minimum value, called the quadrature-axis position. With the rotor in the direct-axis position and rated current flowing, $X_d'' = 1/2$ the ratio of applied voltage to line current.

Transient Reactance X_d' (Low Current Value) from Locked Line-to-Line Tests. Only for machines without additional rotor circuits—hence only for salient-pole machines without dampers—does this test measure

X_d'. Made at low currents, it gives the unsaturated value which, when multiplied by the empirical factor 0.88 (See Appendix VIII) gives, approximately, the saturated value. Made at high currents, the saturated value may not result, because saturated conditions are caused by both armature current and field excitation, and the latter is not present in this test.

Transient Reactance X_d' by an Indirect Method. It has been shown that[5]

$$X_d' = \frac{T_d'}{T_{do}'} X_d.$$

On the basis of tests performed, it is stated in Appendix VIII that the ratio of saturated to unsaturated values of X_d' and of T_d' may be taken as 0.88; accordingly,

$$X_d' \begin{pmatrix}\text{saturated}\\ \text{value}\end{pmatrix} = 0.88 \; \frac{T_d' \begin{pmatrix}\text{unsaturated}\\ \text{value}\end{pmatrix}}{T_{do}'} X_d \tag{1}$$

$$= \frac{T_d' \begin{pmatrix}\text{saturated}\\ \text{value}\end{pmatrix}}{T_{do}'} X_d \tag{2}$$

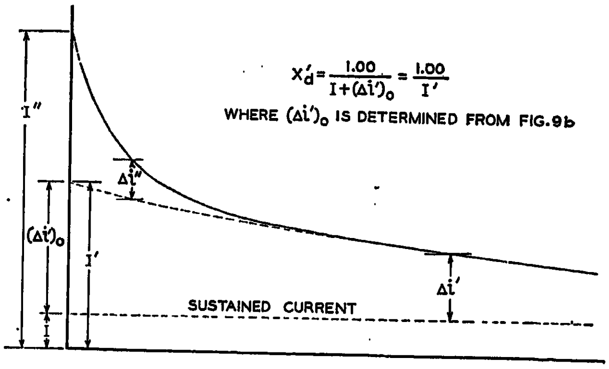

Fig. 9a—Transient Reactance

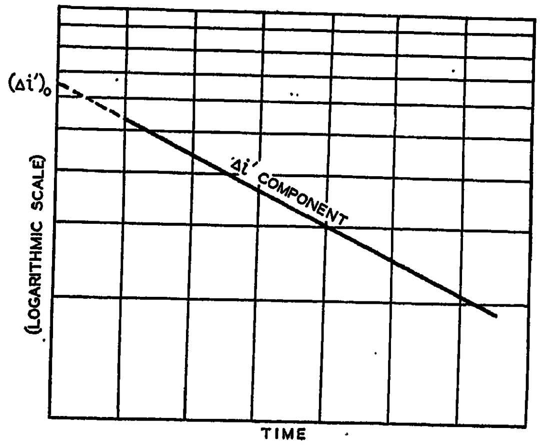

Fig. 9b—Extrapolation of $\Delta i'$ Component of Fig. 9a

Quadrature-Axis Reactances

Synchronous Reactance X_q. The unsaturated value is obtained from the slip test at the same time that X_d is measured. With the rotor magnetized in the quadrature axis, as evidenced by positive or negative peak voltage across the field, X_q is the ratio of applied voltage to line current. See Fig. 5. A method of determining the saturated value is given in Appendix I. For salient-pole machines without dampers, the locked line-to-line test, with readings taken at low currents in the quadrature-axis position, also determines X_q.

Transient Reactance X_q'. Since salient-pole machines have no effective quadrature-axis rotor circuit, $X_q' = X_q$. The turbine generator is the only common example of a machine having effective quadrature-axis circuits, and for most practical purposes, and particularly for short-circuit calculations, X_q' may be taken $= X_d'$ (saturated values). Appendix II gives a method of measuring the saturated value, and Appendix III a method for a low-current value.

Subtransient Reactance X_q'' from Locked Line-to-Line Test. The remarks given under the corresponding test for X_d'' apply here. That is, this test is normally useful only for low-current values of X_q'', which for salient-pole machines with dampers equals approximately the saturated value. For turbine generators the saturated value of X_q'' may be taken equal to that of X_d''. Appendix IV discusses the direct determination of X_q'' (saturated value) from short circuit.

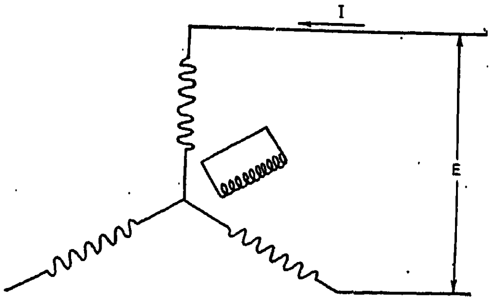

Fig. 10—Locked Line-to-Line Test. For Subtransient Reactances

$X_d'' = E/2\,I$ for direct axis position
$X_q'' = E/2\,I$ for quadrature axis position
E = applied single-phase voltage

To measure X_q'' (low-current value) the procedure is similar to that for the corresponding X_d'' test. With the rotor in the quadrature-axis position and about rated current flowing, X_q'' is ½ the ratio of applied voltage to line current. See Fig. 10. Serious rotor heating may result with turbine generators.

Zero-Sequence Reactance X_0

Locked Zero-Sequence Reactance Test. With the field winding closed on itself and the rotor at standstill, single-phase voltage is applied to the phases connected either in series (Fig. 11a) or parallel (Fig. 11b); with approximately rated current per phase circulating, zero-sequence impedance is the ratio of voltage per phase to current per phase. If the resistance component is small, this ratio may be taken as X_0. This reactance is a minimum for a ⅔ pitch armature winding, and if the pitch is near this value, making X_0 low, the series connection has an advantage over the parallel connection since the latter requires a source of relatively high current at low voltage. Results in Part III show that X_0 is little affected by whether the rotor is running or at standstill.

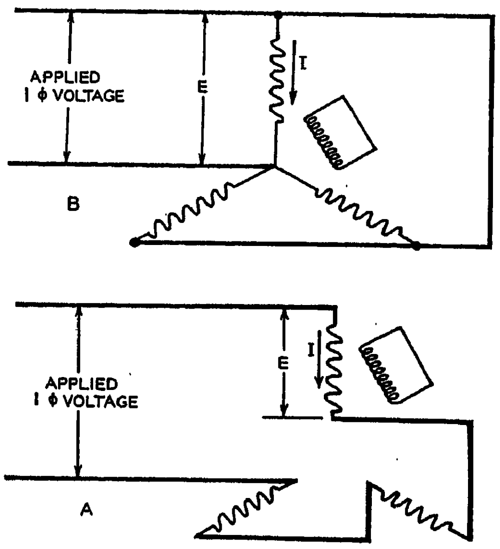

Fig. 11—Locked Zero-Sequence Reactance Test
$X_0 \approx E/I$

A—Series connection
B—Parallel connection

X_0 from Sustained Double Line-to-Neutral Short Circuit. The locked test above may be at a disadvantage due to the requirement of a source of single-phase power. The method to be described, believed to be presented for the first time, is developed in Appendix V; it has the advantage that no source of single-phase power is required, and the disadvantage that serious rotor heating may result with turbine generators, due to the flow of negative-sequence current. See Fig. 12. It is shown in Appendix V that with a double line-to-neutral short circuit at the terminals,

$$\check{Z}_0 = -\frac{\check{E}_a}{\check{I}_n} \tag{3}$$

where $\check{E}_a$ = voltage on the open phase.
$\check{I}_n$ = neutral current.

If the resistance component is small,

$$X_0 \approx \frac{E_a}{I_n} \tag{4}$$

Since X_0 is the value effective when zero-sequence current equals rated current, the field current should be adjusted to give a value of $I_n = 3$ times rated current, but good results may be obtained at lower current.

Note: As in all sustained short circuits, the high currents associated with sudden short circuits are avoided if the short circuit is applied with no field current flowing, and then the field current built up and adjusted to give the desired armature current.

Negative-Sequence Reactance X_2 [16]

The variation of X_2, depending on whether the negative-sequence voltage or current is fundamental, is discussed in Appendix VI. In general, X_2 may be taken as the arithmetical average of X_d'' and X_q'', this being the value obtaining when fundamental current is circulated. For salient-pole machines, X_d'' and X_q'' as determined from a locked line-to-line test can be averaged to give X_2. For turbine generators, X_2 must be the average of certain saturated values of X_d'' and X_q'', which values are usually not obtained from the locked line-to-line test; however, as concluded in a discussion in Part III, it may be said that for turbine generators, $X_d'' = X_q'' = X_2$ (saturated values).

X_2 from Sustained Line-to-Line Short Circuit. This test is practical for salient-pole machines with dampers and gives fair results for salient-pole machines without dampers. It is shown in Appendix VII that with a line-to-line short circuit on phases b and c, at machine terminals (Fig. 13), the negative-sequence impedance

$$\check{Z}_2 = \frac{-j}{\sqrt{3}} \frac{\check{E}_{ab}}{\check{I}_b} \tag{5}$$

where $\check{E}_{ab}$ = line-to-line voltage.
$\check{I}_b$ = short-circuit current.

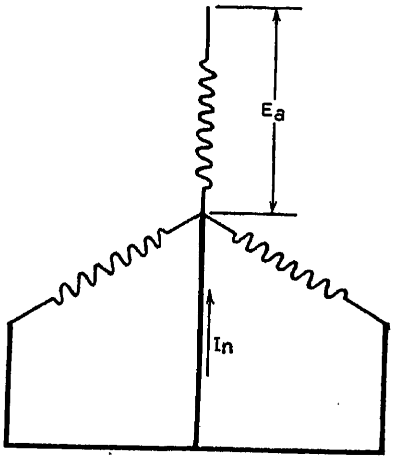

Fig. 12—X_0 from Double Line-to-Neutral Short Circuit
$X_0 \sim \frac{E_a}{I_n}$

If W_2 = watts measured using E_{ab} and I_b,

$$X_2 = \frac{E_{ab}}{\sqrt{3}\, I_b} \cdot \frac{W_2}{E_{ab}\, I_b} \tag{6}$$

If $W_2 \approx E_{ab}\, I_b$ which means a negligible resistance component,

$$X_2 \approx \frac{E_{ab}}{\sqrt{3}\, I_b} \tag{7}$$

There should be no appreciable external resistance or inductance in the field circuit, particularly for salient-pole machines without dampers. The test is made with negative-sequence current equal to rated current, hence armature current is 1.73 (per unit value). For turbine generators, such a current value may result in serious rotor heating, hence it is usually best to take readings at lower currents, and extrapolate the results.

TIME CONSTANTS

Consider a coil having constant inductance L (henrys or abhenrys) and constant resistance R (ohms or abohms). If it is short-circuited on itself at any instant at which it carries current I, the current decays according to the familiar exponential expression $i = I/\epsilon^{t/T}$ where i is the current at time t seconds, $T = L/R$ seconds, and $\epsilon = 2.718$ = base of Napierian logarithms. If $t = T$, $i = I/\epsilon = 0.368\,I$ hence the time constant may be defined either as the ratio L/R, or as the time in seconds for a decaying non-sustained current to decrease to 0.368 of its initial value, assuming exponential decay.

In synchronous machines the rotor circuits are not all concentrated, and saturation exists to various degrees, hence current and voltage changes may not be exponential. In a majority of cases, however, it is found that good approximation is obtained by fitting exponential curves to the actual curves, giving more weight to the initial portions when the changing components are large. Convenient use is made of the fact that an exponentially decaying quantity is a straight line when plotted on semi-log paper; two points which conveniently determine this line are the value I at zero time and the value 0.368 I at time equal to the time constant. It is a very significant fact that a comparison between actual component and fitted exponential is deceiving if made of their semi-log plots; comparison should always be made of Cartesian coordinate plots of actual and fitted curves.

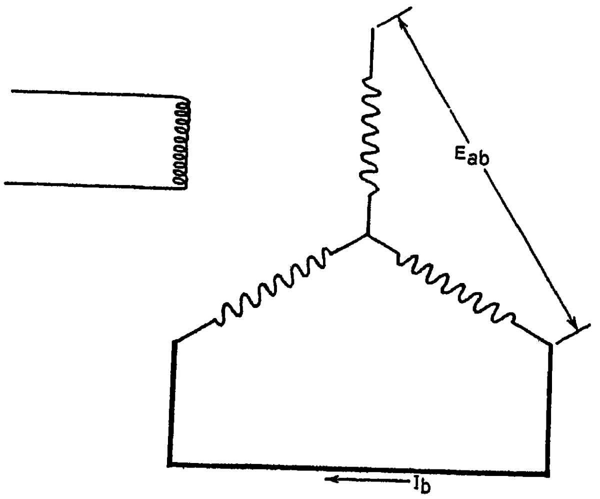

FIG. 13—X_2 FROM LINE-TO-LINE SHORT CIRCUIT

$$X_2 = \frac{E_{ab}}{\sqrt{3}\,I_b}$$

Armature Short-Circuit Time Constant T_a. This time constant applies to both the d-c. and second-harmonic components of the asymmetrical component of armature current (see Bibliography 4—Part V). As shown in Part III, the asymmetrical component of three-phase short-circuit current may not decay with the same time constant, in all three phases. For simplicity, T_a will be taken as the time constant of that one of the two largest components which has initially the most gradual slope. For example, in Fig. 7A, T_a is taken as the time in seconds for the (asymmetrical) current in phase a to decrease to 0.368 of its initial value.

An alternative means of measuring T_a, not satisfactory for turbine generators, is to circulate direct current in two (or three) phases, by applying d-c. voltage between two terminals (or between two terminals tied together and the third); the rotor is driven at rated speed; then when the terminals are short-circuited, T_a is the time for current to decay to 0.368 of its initial value.

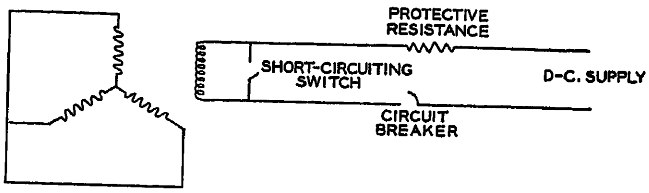

FIG. 14—CONNECTIONS FOR FIELD DECREMENT TEST

Determination of T_d'. (Armature is short-circuited all during test; field is suddenly short-circuited)

Or, knowing the d-c. resistance of the armature r_a, and X_2 (saturated value), T_a may be computed from[5]

$$T_a = \frac{1}{2\,\pi f}\,\frac{X_2}{r_a} \qquad (8)$$

Where f = rated frequency and X_2 and r_a are in the same units.

DIRECT-AXIS TIME CONSTANTS

Short-Circuit Transient Time Constant T_d'. This is the time constant of the field circuit with the armature short-circuited, hence is the time-constant of the $\Delta\, i'$ component in Fig. 9A, and is readily determined from the plot in Fig. 9B. It is the saturated value that is thus obtained from analysis of a dead three-phase short-circuit from rated voltage at no load. External resistance or inductance in the field circuit affects field-current decrement, hence the ideal condition for determining T_d' directly is to have the field current supplied from an infinite d-c. bus. In practise, it is desirable to have negligible external inductance and resistance in the field circuit, as obtained by use of a compensated exciter.

Theoretically, the variation of $\Delta\, i'$ should be exponential only for a state of no saturation. Tests show, however, that under short circuit, a single exponential curve will usually fit $\Delta\, i'$ out to where it has reached about ¼ of its initial value, and for that reason, and until a more accurate and sufficiently simple analysis is available, it is proposed that the time constant of the fitted exponential be used.

T_d' from Short-Circuit Field-Decrement Test. This is a simple method of measuring the unsaturated value of T_d' for salient-pole machines but is generally unsatisfactory for turbine generators. See Fig. 14. With a sustained three-phase short circuit at machine terminals and a fraction (about ½) of rated current flowing, the field winding is suddenly short-circuited on itself, and an oscillographic record made of armature and field currents, the latter being recorded because it usually has a sudden initial change which helps in fixing zero time. A semi-log plot of armature current then gives T_d' (unsaturated). This value times 0.88 gives approximately the saturated value (see Appendix VIII).

T_{do}' from Open-Circuit Field-Decrement Test. This is the time constant of the field circuit with the armature open. As with the similar test for T_d', this test is convenient for salient-pole machines but is generally unsatisfactory for turbine generators. See Fig. 15. With the machine running at about ½ rated voltage at no load, the field winding is suddenly short-circuited on itself, and armature voltage and field current recorded by oscillograph. T_{do}' is determined from a semi-log plot of armature voltage.

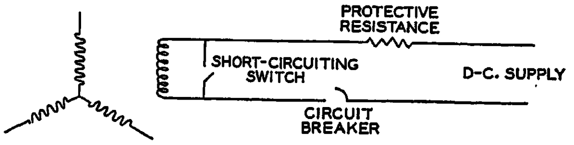

Fig. 15—Connections for Field Decrement Test

Determination of T_{do}'. (Armature is open)

Short-Circuit Subtransient Time Constant T_d''. This, like T_{do}'', has significance only for machines with additional rotor circuits; it is the time constant of the $\Delta i''$ component in Fig. 9A. This component may sometimes be only roughly approximated by a fitted exponential. A semi-log plot is made of $\Delta i''$ and a straight line fitted to it. In Part III, Fig. 21 shows the good accuracy obtained by fitting an exponential to $\Delta i''$ for a large turbine generator.

Open-Circuit Subtransient Time Constant T_{do}''. This can be obtained from a modification of the slip test with the field winding closed on itself; the rotor is magnetized in the direct axis, the applied voltage suddenly disconnected, and terminal voltage recorded by oscillograph. From a semi-log plot of voltage, the slowly decaying component is determined; the difference between the total voltage and the slowly decaying component is plotted on semi-log paper and the time constant of the fitted exponential is T_{do}''.

QUADRATURE-AXIS TIME CONSTANTS

Short-Circuit Transient Time Constant T_q'. This constant, like T_{qo}', has practical significance only in case of turbine generators; it can be determined from the same test used for X_q' (Appendix II). Rated current is circulated as in the slip test, and when the rotor is magnetized in the quadrature axis, a three-phase short circuit is applied. T_q' is obtained from a semi-log plot of the symmetrical component of current, neglecting the rapidly decaying initial portion.

Open-Circuit Transient Time Constant T_{qo}'. This can be determined from the same voltage-decrement test made for the low-current value of X_q' (See Appendix III), as the time constant of voltage decrement, neglecting the initial rapidly-decaying portion.

Short-Circuit Subtransient Time Constant T_q''. This constant, like T_{qo}'', has significance only for turbine generators and salient-pole machines with dampers; it is determined from the same test used for X_q' and T_q' as the time constant of the difference between the total short-circuit current and the slowly-decaying component.

Open-Circuit Subtransient Time Constant T_{qo}''. This is determined from the same voltage-decrement test used for T_{qo}' (See Appendix III) as the time constant of the difference between total voltage and its slowly-decaying component.

RESISTANCES

The zero-, positive-, and negative-sequence resistances are simply the resistance components of the corresponding sequence impedances. For example, when negative-sequence current is circulated, the reactive component of negative-sequence voltage ÷ circulated current is X_2, and the in-phase component of voltage ÷ the current is R_2. Of the three sequence resistances R_2 is usually the only one which may sometimes be important and is therefore the only one discussed.

The loss associated with negative-sequence current may not vary as the square of the current, particularly with turbine generators, because of various effects such as those caused by saturation, skin effect, and depth of penetration of flux in solid material. It may sometimes be necessary, with turbine generators particularly, that the variation of loss with current be determined and R_2 used as a loss coefficient rather than as a simple resistance. *In all cases, R_2 will be considered as that value effective at rated negative-sequence current.* Tests indicate that this loss varies approximately as the 1.8 power of negative-sequence current, for turbine generators, for current of the order of rated current. Unless such a machine is designed for single-phase operation, such a value of current may cause serious rotor heating when maintained for anything more than a short time; results obtained at low-current values can be extrapolated. In the tests below there should be no external resistance or inductance in the field circuit, especially for salient-pole machines without dampers.

R_2 from Loss Measurement. In general, the most accurate and practical means of determining R_2 is by actual measurement of energy loss in a sustained line-to-line short circuit. This may be accomplished by a retardation test; by measurement of shaft input under

two conditions—at no load, and with the machine short-circuited (line-to-line). C. F. Wagner has thoroughly analyzed the distribution and significance of negative-sequence loss and shown,[10] based on certain well warranted assumptions, that

$$R_2 = \frac{\text{Net Shaft Input}}{2\, I_2^2} \qquad (9)$$

which can be written

$$R_2 = 1.5 \frac{\text{Net Shaft Input}}{I_b^2} \qquad (10)$$

Where

I_2 = negative-sequence current.
= $0.577\, I_b$.
I_b = line-to-line short-circuit current.
Net Shaft Input = (Prime-mover input while machine is short-circuited.
− Prime-mover input at no load.
− Prime-mover losses.
− Friction and windage losses).

If practical and not per unit values are used, the input per phase, or ⅓ the net shaft input, is used. If loss is measured by a retardation test, net shaft input becomes the total short-circuit loss minus windage and friction loss. In terms of the sequence networks,[13,14] $I_2^2\, R_2$ is electrical power input when a machine carries negative-sequence current I_2; in addition there is shaft (torque) input which is less than $I_2^2\, R_2$, being more accurately equal to I_2^2 times (R_2 minus the stator resistance), but in general it is sufficiently accurate to take shaft input = $I_2^2\, R_2$. It is well to note that regardless of the latter assumption, in system studies the electrical input must be considered separately from the direct shaft input whenever more than one machine is involved, because while direct shaft input is supplied by the machine itself, electrical input may be divided between different machines.

R_2 from Wattmeter Measurement. The accuracy of this alternative method depends critically upon the accuracy of voltage, current, and watt measurements. Refer to Fig. 13. With a sustained line-to-line short circuit at machine terminals (as in the test above), and with short-circuit current = 1.73 times rated current, we may write—from formulas in Appendix VII,

$$R_2 = \frac{E_{ab}}{\sqrt{3}\, I_b} \sqrt{1 - \left(\frac{W_2}{E_{ab}\, I_b}\right)^2} \qquad (11)$$

Where

E_{ab} = line-to-line voltage.
I_b = short-circuit current.
W_2 = measurement of watts obtained by using E_{ab} and I_b.

III—Illustrations of Application of Test Methods

This part deals with descriptions of tests made in accordance with methods described in Part II. Illustrations are given not of all the methods previously described, but of those which concern the more important constants—such as direct-axis reactances and time constants.

General Description of Test Facilities and Set-Up. Tests were made with those facilities available in the company with which the author is associated. The usual precautions were taken relative to indicating instruments, and particular care was exercised in oscillographic measurements since many important constants are determined by oscillogram analysis. Appreciating the fact that currents in sudden short circuits contain large asymmetrical components which might saturate current transformers, three non-inductive shunts[15] were employed (Fig. 16) for most sudden short-circuits. Each shunt consists of two brass cylinders separated by mica and sweated together at one end; the inner cylinder is tapped by two soldered connections which lead to the oscillograph.

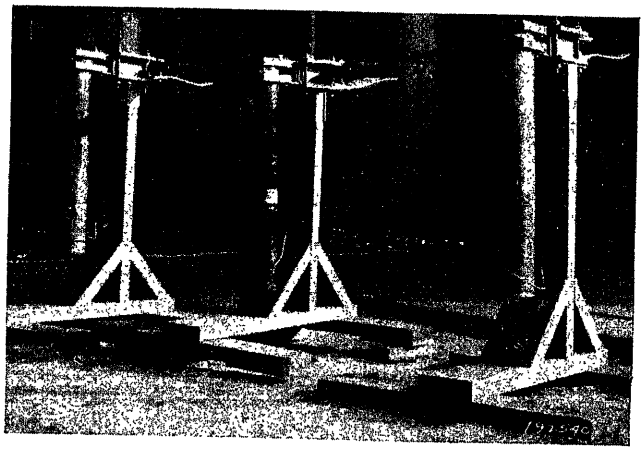

FIG. 16—NON-INDUCTIVE CURRENT SHUNTS

Sustained short circuits were made with armature terminals short-circuited with short connecting links bolted in place with the machine at standstill; the condition of sustained short circuit was obtained by driving the machine at rated speed and then applying field current, thus eliminating the high currents associated with sudden short circuits. The latter were effected by a standard three-phase 0-30 circuit breaker (Fig. 17). The shunts were mounted on a platform built on the side of the breaker structure. For the safety of the oscillograph operator the shunts were grounded as shown in Fig. 18.

To eliminate the necessity of a prime mover in the sudden short circuits of larger machines, it was often convenient to run the machine as a motor at unity power factor at or above synchronous speed, then to suddenly disconnect the power supply and apply the short circuit as the machine reached synchronous speed; this allows a speed decrease, but does not affect the current magnitude appreciably because both generated voltage and reactance decrease with frequency. In all such tests, a constant-frequency timing wave was recorded.

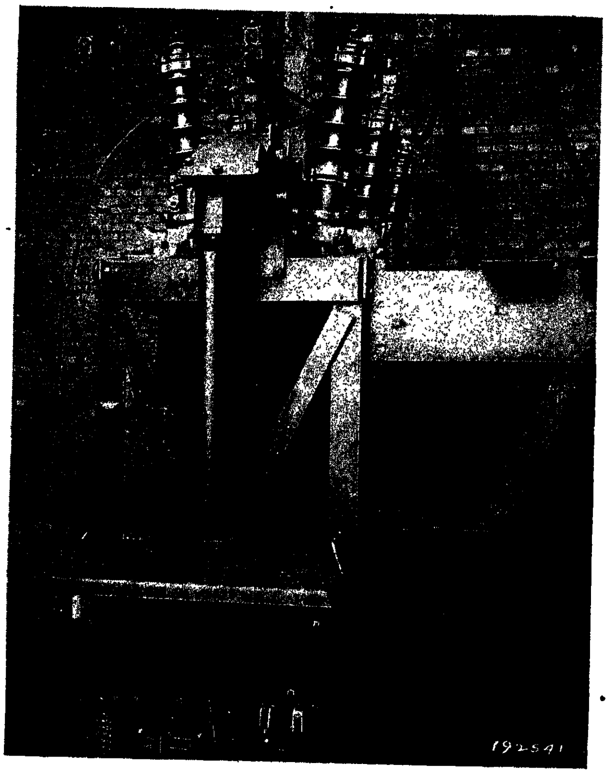

FIG. 17—CIRCUIT BREAKER USED IN SUDDEN SHORT-CIRCUIT TEST

Synchronous Reactances X_d and X_q. Table I gives some values of X_d and X_q as obtained from slip tests, also values of X_d determined from saturation curves.

TABLE I

Machine	X_d From sat. curves	X_d From slip test	X_q From slip test	Voltage applied in slip test
Turbine generator (18,750 kva.)	1.15	1.10	1.10	0.35
Synchronous motor (750 hp.)	1.30	1.35	.97	0.50
Salient-pole generator (100 kva.)	1.25	1.25	.87	0.48

X_d' and X_d'' from a Three-Phase Short-Circuit at Rated Voltage No Load. A test on a 75,000-kva. turbine generator will be described. The oscillogram in Fig. 19 is of a dead three-phase short circuit at rated voltage (11,600 volts). Current in each phase is first separated into symmetrical and asymmetrical components (the latter is d-c. only, since $X_d'' = X_q''$). Fig. 20A is a semi-log plot of the d-c. components and gives the initial values 9.00, 8.20, and 1.80, which when multiplied by averaging factors determined from the symmetrical components, give the corrected values 9.13, 7.79, and 1.85. Fig. 20B gives the initial value of the maximum possible d-c. component = 9.85. The initial value of a-c. (subtransient current) is $I'' = 9.85/\sqrt{2} = 6.96$; speed and voltage just previous to short circuit were normal,* hence

$$X_d'' = \frac{\text{Voltage}}{I''} = \frac{1.00}{6.96} = 0.144 \text{ (or 14.4 per cent)}$$

The symmetrical components are plotted in Fig. 21 and an average curve drawn. Sustained current $I = 1.07$, shown as a dotted horizontal line. A semi-log plot of $\Delta i'$ in Fig. 22A gives the extrapolated initial value $(\Delta i')_0$ which is replotted in Fig. 21. The initial transient current $= I' = I + (\Delta i')_0 = 4.20$, hence

$$X_d' = \frac{\text{Voltage}}{I'} = \frac{1.00}{4.20} = 0.238 \text{ (or 23.8 per cent)}$$

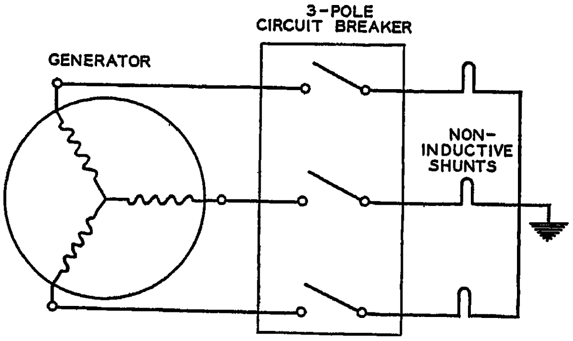

FIG. 18—DIAGRAM FOR THREE-PHASE SHORT-CIRCUIT TESTS

FIG. 19—FIRST 0.5 SEC. OF OSCILLOGRAM OF THREE-PHASE SHORT CIRCUIT AT RATED VOLTAGE, NO LOAD, 75,000-KVA. TURBINE GENERATOR

Highest peak current = 75,000 amperes. Note that the current in the bottom wave does not go through zero until several cycles after the short circuit; this is due to the fact that the asymmetrical component has initially a slower decrement than the symmetrical component

X_d'' from Locked Line-to-Line Test. The important effect of saturation on X_d'' for turbine generators is illustrated by Fig. 23, where reactance values at currents less than 2.0 were obtained from locked line-to-line tests, and those at higher currents from sudden three-phase short circuits. This also illustrates the

---

*If speed is not synchronous at instant of short circuit, the voltage used in computing X_d' and X_d'' should be read from the no-load saturation curve for the existing field current.

inadequacy of this locked test for the determination of X_d'' for turbine generators.

Fig. 24 shows the small difference between saturated and low-current values of X_d'' for salient-pole machines.

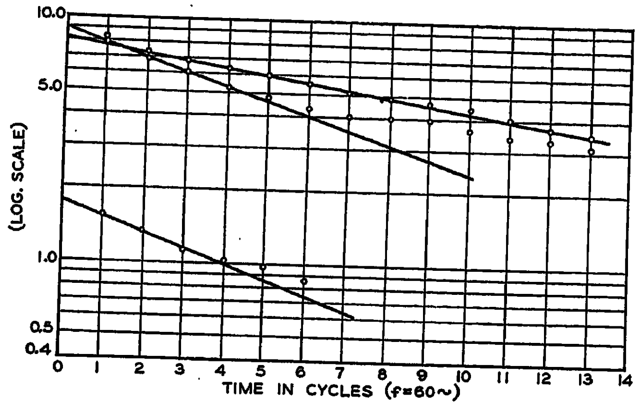

FIG. 20A—ASYMMETRICAL COMPONENTS FROM FIG. 19

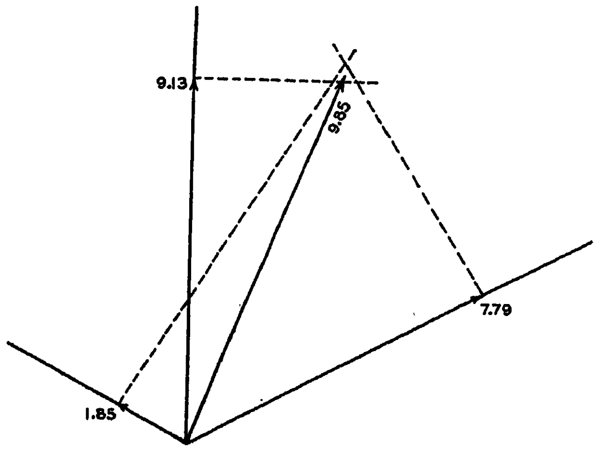

FIG. 20B—MAXIMUM POSSIBLE ASYMMETRICAL COMPONENT

(Instantaneous value)

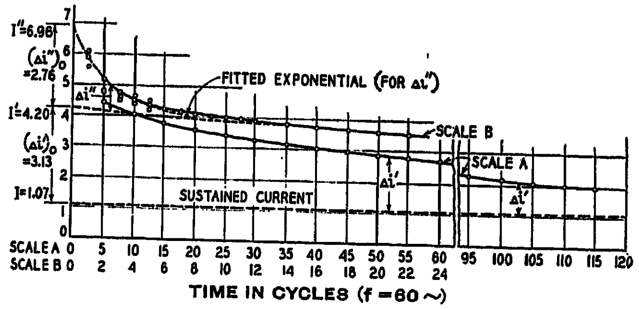

FIG. 21—SYMMETRICAL A-C. COMPONENT TAKEN FROM WAVE IN FIG. 19

$$X_d'' = \frac{1.00}{6.96} = 0.144$$

$$X_d' = \frac{1.00}{4.20} = 0.238$$

It is important to note that the value obtained at about rated current from this locked test is essentially the same as the saturated value obtained from a dead three-phase short circuit from rated voltage at no load.

X_q for Salient-Pole Machines without Dampers. X_q (unsaturated value) is determined from the locked line-to-line test at low currents (¼ or less). Fig. 25

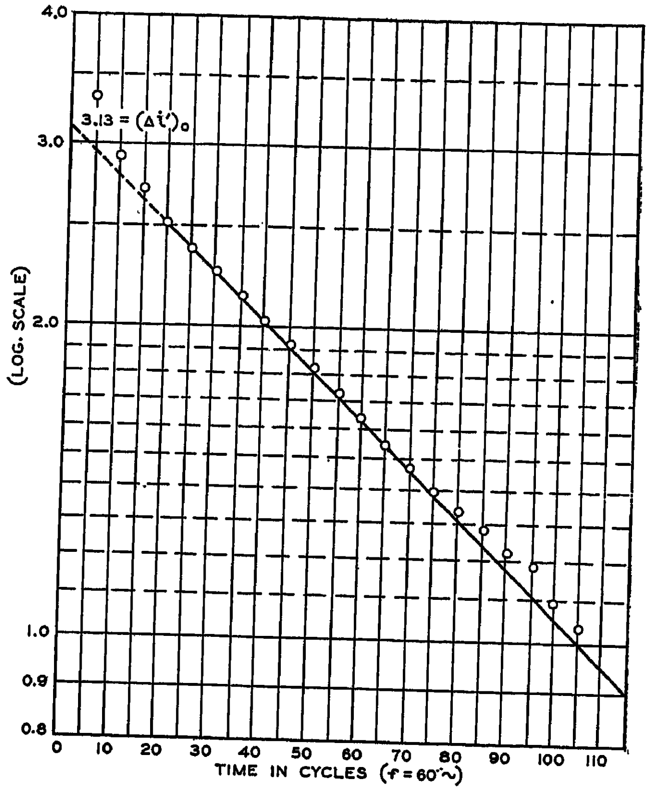

FIG 22A—Δ i' COMPONENT

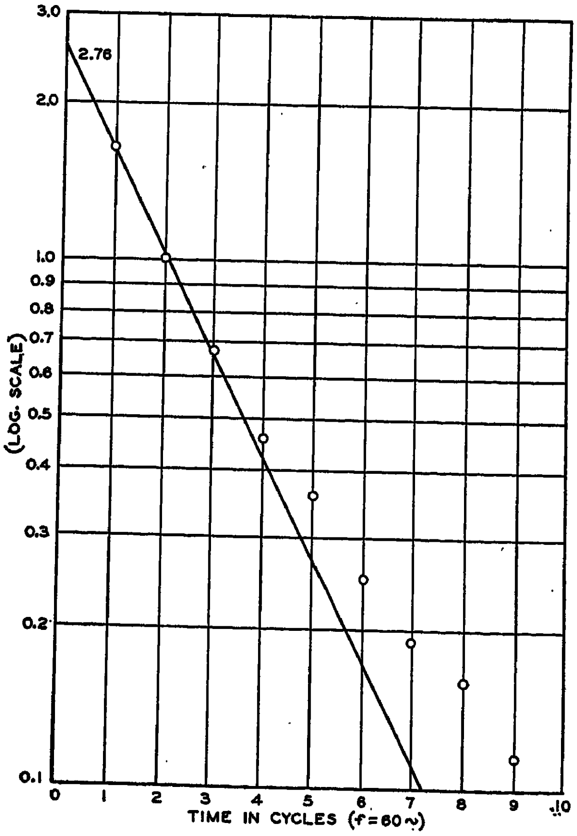

FIG. 22B—Δ i'' COMPONENT

shows saturation effects at higher currents. When operating under load, the reduction in X_q may be still greater (Appendix I).

Low-Current Value of X_q' for a Turbine Generator. This was measured on an 18,750-kva. turbine generator by the method in Appendix III. Fig. 26 shows terminal voltage decrement. A semi-log plot in Fig. 27A gives $E' = 0.185$. Also, $E = 0.378$ and $I = 0.379$, and applying formula (2) from Appendix III,

$$X_q' = \frac{E - E'}{I} = \frac{0.378 - 0.185}{0.379} = 0.51 \text{ (low-current value)}$$

A similar direct axis test gave $X_d' = 0.40$, whereas the saturated value of $X_d' = 0.14$. This large difference between 0.14 and 0.40 may be attributed largely to rotor saturation effects.

X_q'' for Turbine Generators. For such machines, the ratio X_q''/X_d'' varies from about 1.0 under saturated conditions to 1.3 for low-current values. Fig. 28A shows X_q'' at low currents, for a 75,000-kva. turbine generator, as found from the locked line-to-line test. In order to study the relative values of X_d'' and X_q'' at high currents, line-to-line short circuits at rated voltage were made on several turbine generators; these tests indicated that at high values of current (sudden short-circuit values), $X_d'' = X_q'' = X_2$.

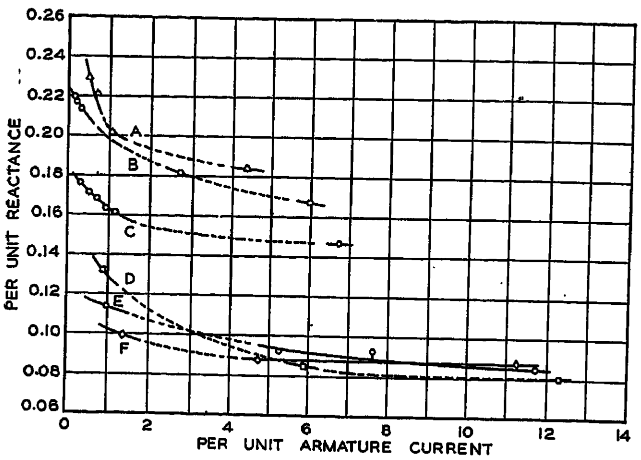

FIG. 23—VARIATION OF X_d'' WITH CURRENT FOR TURBINE GENERATORS

A = 3,125 kva. turbine generators
B = 43,750 kva. turbine generators
C = 75,000 kva. turbine generators
D = 9,375 kva. turbine generators
E = 18,750 kva. turbine generators
F = 12,500 kva. turbine generators

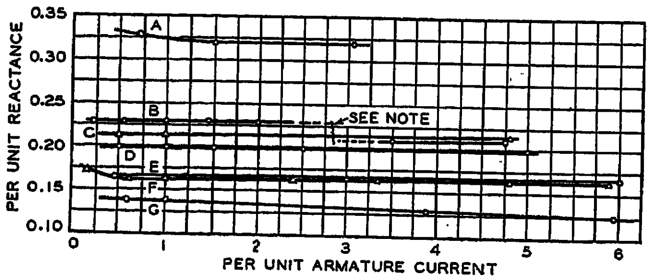

FIG. 24—X_d'' FOR SALIENT-POLE MACHINES WITH DAMPERS

A = 240 kva. synchronous motor
B = 730 kva. synchronous motor
C = 15,000 kva. synchronous condenser
D = 30,000 kva. synchronous condenser
E = 100 kva. generator
F = 331 kva. synchronous motor
G = 5,000 kva. generator
NOTE: This apparent break is attributed to errors

Zero-Sequence Reactance X_0. Fig. 29 shows the small effect of saturation on X_0 for turbine generators, at lower currents, as obtained from a locked zero-sequence reactance test. For the 75,000-kva. machine, $X_0 = 0.105$ at rated current; from a sustained double line-to-neutral short-circuit test, $X_0 = 0.098$. The data in Table II afford comparison of values measured with the rotor at standstill and driven at rated speed.

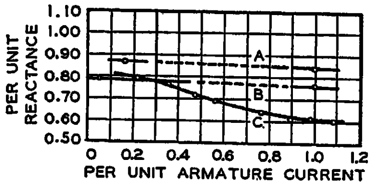

FIG. 25—X_q FOR SALIENT-POLE MACHINES WITHOUT DAMPERS

A = 7,500-kva. generators
B = 750-kva. generator
C = 331-kva. synchronous motors with dampers off

TABLE II—ZERO-SEQUENCE REACTANCE X_0

	Machine 1	Machine 2
Rotor running	0.0290	0.0158
Rotor at standstill	0.0306	0.0163

Negative-Sequence Reactance X_2. As stated in Part II, X_2 for salient-pole machines with dampers can be computed as the average of X_d'' and X_q'' measured at rated current by a locked line-to-line test. Values so computed, and values obtained from the sustained line-to-line test, are tabulated in Table III.

TABLE III—X_2 FOR TYPICAL SALIENT-POLE MACHINES (WITH DAMPERS AND END RINGS)

(1/2) $(X_d'' + X_q'')$ (X_d'' and X_q'' from locked line-to-line test)	$X_2 = E_{ab}/\sqrt{3}\,I_b$ From sustained line-to-line short circuit
0.34	0.34
0.160	0.150
0.23	0.21
0.20	0.20
0.17	0.180
0.135	0.130
0.165	0.160
0.160	0.160
0.24	0.25
0.23	0.23
0.21	0.20
0.195	0.195
0.120	0.120

Armature Short-Circuit Time Constant T_a. In Fig. 20A, that one of the two largest asymmetrical components which has the most gradual initial slope has an initial value of 8.20 and a time constant = 15.5 cycles = 0.26 sec. Hence T_a = 0.26 sec. for this 75,000-kva. turbine generator.

Time Constants T_d' and T_d''. For this same machine, T_d' = 1.53 sec. (saturated value) from Fig. 22A. The fact that field-decrement tests give indefinite results (non-exponential decay) for turbine generators is illustrated by Fig. 30, which is for a 9,375-kva. turbine generator. Fig. 31 shows corresponding curves for a large salient-pole generator, illustrating that for salient-pole machines, this test is quite satisfactory; the unsaturated value of T_d' from a short-circuit field-decrement test when multiplied by 0.88 gives the saturated value, approximately.

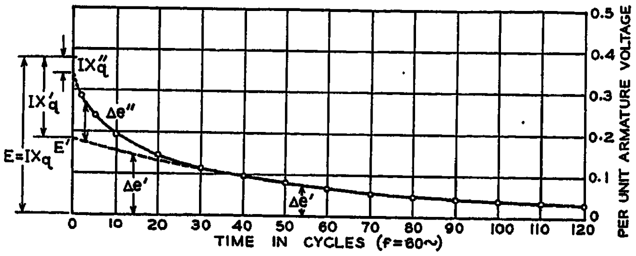

FIG. 26—QUADRATURE-AXIS DECREMENT

18,750-kva. turbine generator

Short-Circuit Subtransient Time Constant T_d''. Refer to Fig. 21 for the test on a 75,000-kva. turbine generator. A semi-log plot of Δ i'' made in Fig. 22B gives the time constant of a fitted exponential as T_d'' = 2.1 cycles = 0.035 sec. Note that the large discrepancy appearing in Fig. 22B, between actual Δ i'' component and the fitted exponential, is really quite negligible when they are replotted in Fig. 21 in Cartesian coordinates.

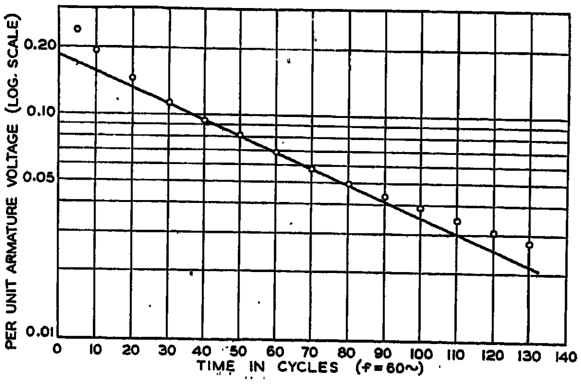

FIG. 27—Δ e′ COMPONENT FROM FIG. 26

T_{q0}' = 60 cycles = 1.00 sec

Transient Time Constant T_{q0}'. (See Appendix III.) Refer to Fig. 26 (for an 18,750-kva. turbine generator); the Δ e' component is plotted in Fig. 27, and in this particular case an exponential approximates it very closely, giving T_{q0}' = 1.00 sec. for this low voltage. Had this test been made at higher voltage it is doubtful if any fitted exponential would be other than roughly approximate.

Negative-Sequence Resistance R_2. In keeping with a previous statement, all values quoted are those effective when negative-sequence current equals rated current. A 5,000-kva. salient-pole machine gave R_2 = 0.120 by prime-mover input measurement, and R_2 = 0.135 by wattmeter measurement. On the other hand, with a 7,500-kva. waterwheel type generator without dampers, R_2 from wattmeter measurements was in considerable error, but R_2 = 0.033 was obtained from both the retardation test and a measurement of prime-mover input (for a line-to-line short circuit). For both machines above, loss was found to vary as the square of the current; this is, of course, affected by rotor temperature.

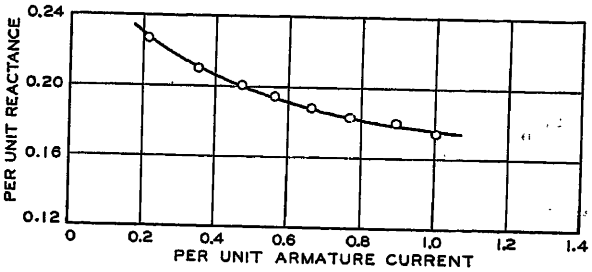

FIG. 28—VARIATION OF X_q'' FOR A TURBINE GENERATOR (75,000 KVA.)

Measurements on turbine generators indicate a variation of negative-sequence loss as the 1.8 power of current. Since part of the loss varies as the 1.5 power and part as the square of the current, this result is quite reasonable. For example, tests on a 43,750-kva. turbine generator showed a variation as the 1.8 power and the loss associated with direct current in the armature (and rotor driven at rated speed) was found to vary as the 1.8 power at low currents. (For this latter loss, practically all the energy is supplied directly by shaft torque.)

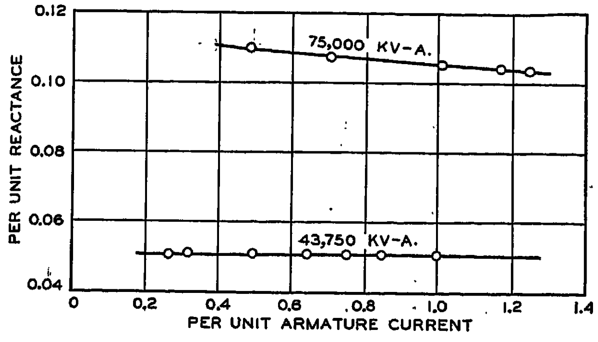

FIG. 29—VARIATION OF X_0 FOR TURBINE GENERATORS

SUMMARY

The tables below form an explicit summary of test results. Table IV lists what are considered to be the more important machine constants. The values of X_d', X_d'', T_d', T_d'' and T_a in Tables V and VI were obtained from three-phase short circuits at rated voltage. Tables VII and VIII give other test values. Table IX gives typical values of various machine constants, based on test results; constants calculated from formulas given in the companion paper by L. A. Kilgore[6] were used in arriving at some of the ranges given.

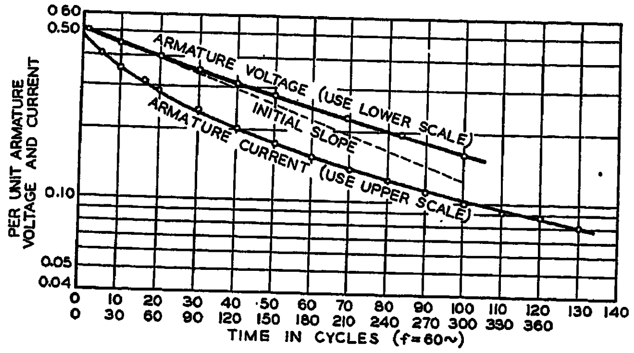

FIG. 30—RESULTS FROM FIELD DECREMENT TESTS ON A 9,375-KVA. TURBINE GENERATOR

ACKNOWLEDGMENTS

The author wishes to thank Messrs. R. D. Evans and C. F. Wagner for valuable criticisms, Mr. C. J. Fechheimer under whose supervision the work was carried out; Mr. C. E. Peck for considerable assistance in test analysis and Mr. C. Gentilini for preparing the illustrations.

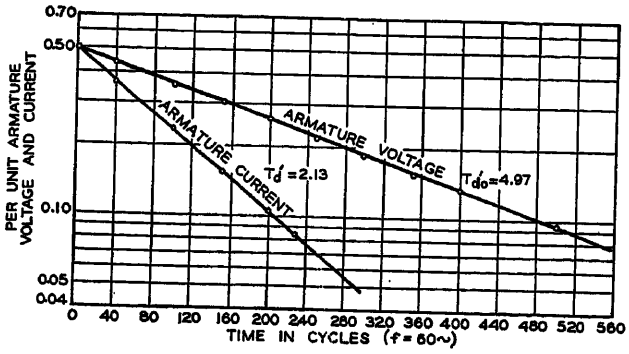

FIG. 31—RESULTS FROM FIELD DECREMENT TESTS ON A 7,500 KVA. WATERWHEEL GENERATOR

Appendix I

QUADRATURE-AXIS SYNCHRONOUS REACTANCE X_q (SATURATED VALUE)

This is a practical method for measuring the saturated value of X_q, based on a relation derived from the application of Blondel's two-reaction theory, and involving measurement of relative angle of the rotor and the terminal voltage vector, while the machine is carrying any load (other than a very low power-factor load)—such as normal load for a generator. Fig. 32 is a vector diagram of a generator supplying a lagging power-factor balanced load; machine resistance is neglected. Let

E_t = terminal voltage (line-to-neutral).
I = load current.
I_d = direct-axis component of load current.
I_q = quadrature-axis component of load current.
e_d = nominal or excitation voltage.
ϕ = $\cos^{-1}$ (power factor).
δ = angle between nominal and terminal voltages.
ψ = angle between nominal voltage and load current.

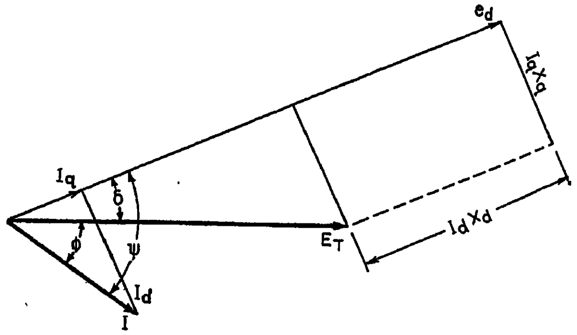

FIG. 32—VECTOR DIAGRAM OF A GENERATOR SUPPLYING A LAGGING POWER-FACTOR LOAD

It is seen from Fig. 32 that

$$\begin{aligned} E_t \sin\delta &= I_q X_q \\ &= (I \cos\psi)\, X_q \\ &= [I \cos(\phi + \delta)]\, X_q \end{aligned}$$

Whence $E_t \sin\delta = I\, X_q\, (\cos\phi \cos\delta - \sin\phi \sin\delta)$
and

$$X_q = \frac{E_t \sin\delta}{I\,(\cos\phi\cos\delta - \sin\phi\sin\delta)}$$

Dividing through by $\sin\delta$ gives

$$X_q = \frac{E_t}{I\,(\cos\phi\cot\delta - \sin\phi)} \qquad (12)$$

TABLE IV—THE MORE IMPORTANT MACHINE CONSTANTS

$^*X_d$ = synchronous reactance
X_d' = transient reactance } = X_1 = positive-sequence reactance
X_d'' = subtransient reactance
$S\,C\,R$ = short-circuit ratio†
X_2 = negative-sequence reactance
X_0 = zero-sequence reactance
T_a = (short-circuit) armature circuit time constant
$^*T_d'$ = short-circuit transient time constant
$^*T_d''$ = short-circuit subtransient time constant
T_{do}' = open-circuit transient time constant

NOTE: T_{do}', the open-circuit transient time constant, may readily be computed from the relation

$$T_{do}' = \frac{X_d}{X_d'}\, T_d'$$

where X_d' and T_d' are both saturated values or are both unsaturated values.

*If a reactance or time constant is not qualified as to direct or quadrature axis, it is ordinarily assumed to be a direct axis value; the subscript *d* or *q* always settles this point as far as the *symbol* is concerned.

†Short-circuit ratio is understood as the value defined in the A. I. E. E. Standards; it is well to note that $S\,C\,R$ is the reciprocal of X_d, if there is no saturation (*i. e.*, if the no-load saturation curve is a straight line).

TABLE V—TURBINE-GENERATOR CONSTANTS FROM TEST

Time constants are in seconds. Impedances are per unit values; multiply by 100 to obtain per cent value. The quantity Ω_N, called "normal ohms," is the number of ohms corresponding to 100 per cent impedance; per unit X or R times Ω_N gives the ohmic values of X and R

Kva.	Freq.	Kv. rated	Amps. rated	R. p. m.	Ω_N	X_d	X_d'	X_d''	X_2	X_0	T_a	T_{do}'*	T_d'	T_d''	R_2
1,875	60	0.60	1,805	3,600	0.192	1.00	0.15	...	...	...Δ Conn.	0.066	2.1	0.31	...	0.035
3,125	60	0.48	3,750	3,600	0.074	0.99	0.21	0.185	0.185	0.17	0.038	2.9	0.61	0.045	0.046
7,500	60	6.6	657	3,600	5.80	1.20	0.165	0.092	0.092	0.0180	0.043	4.1	0.56	0.026	
8,575	60	4.15	1,195	3,600	2.01	0.96	0.120	0.084	0.084	0.0160	0.110	3.5	0.44	0.036	0.029
9,375	60	6.6	820	3,600	4.65	1.10	0.140	0.075	0.075	0.0160	0.085	3.9	0.49	0.034	0.029
12,500	60	11.0	655	3,600	9.71	1.00	0.135	0.088	0.088	0.0090	0.110	4.0	0.54	0.040	
18,750	60	13.8	785	3,600	10.1	1.15	0.140	0.085	0.085	0.031	0.13	4.8	0.59	0.041	0.024
43,750	60	13.8	1,830	1,800	4.36	1.30	0.25	0.170	0.170	0.051	0.28	5.2	1.00	0.021	0.042
68,750	60	13.2	3,000	1,800	2.54	0.97	0.21	0.120	0.120	0.059	0.25	7.4	1.60	0.035	0.025
75,000	60	11.6	3,740	1,800	1.79	1.10	0.24	0.145	0.145	0.100	0.26	7.0	1.53	0.034	0.030

*These are values computed from the relation given in the note in Table IV.

TABLE VI—SALIENT-POLE SYNCHRONOUS MACHINE CONSTANTS FROM TEST

Type(a)	Kva.	Freq.	Kv. rated	Amperes rated	R. p. m.	Ω_N	X_d	X_d'	X_d''	X_2	X_0	T_a	T_{do}'	T_d'	T_d''	R_2
Sync. motor	240	60	2.2	63	277	20.1	1.05	0.42	0.32	0.33	(b)	0.048		(c)	0.010	0.089
Sync. motor	331	60	0.44	435	1200	0.585	1.60	0.23	0.160	0.160	(b)	0.033			0.028	0.064
Sync. motor	730	60	2.3	183	1200	7.25	1.30	0.30	0.21	0.21	(b)	0.110	3.05	0.70	0.030	0.110
Sync. motor (N. D.)	730	60	2.3	183	1200	7.25	1.30	0.30	...	0.45	(b)	0.135	3.08	0.69		0.047
Condenser	15,000	60	11.5	753	900	8.82	1.65	0.34	0.21	0.20	0.110	0.180	8.5	1.85	0.033	0.052
Condenser	20,000	60	11.0	1050	720	6.06	1.60	0.45	0.27	0.26		0.21	7.1*	2.0	0.045	0.060
Condenser	30,000	60	10.0	1732	720	3.33	1.50	0.37	0.190	0.180	0.072	0.130	11.3*	2,8	0.030	0.034
Generator	100	60	2.3	25.2	1200	52.7	1.25	0.24	0.165	0.170	0.033	0.023	1.15*	0.22	0.022	0.0170
Generator	5,000	60	7.6	380	900	11.6	0.90	0.22	0.130	0.130	0.063	0.095	3.7*	0.90	0.028	0.0180
H. W. W. Gen. (N. D.)	750	25	6.6	65.6	187.5	58.1	1.20	0.41	...	0.62	(b)	0.18		(c)		0.032
V. W. W. Gen.	39,000	60	13.8	1632	138.5	4.89	.80	...	...	..	..		7.07	3.17(d)		0.078

(a) All machines except those marked (N. D.) have dampers and end-rings.

(b) No neutral available.

(c) Value omitted because tests were made with unmeasured value of external resistance in field circuit.

(d) Unsaturated value from field decrement test.

*These are values computed from the relation given in the note in Table IV.

TABLE VII(a)—THREE-PHASE SYNCHRONOUS MACHINE CONSTANTS, FROM TEST*

Salient-Pole Machines with Dampers (and End-Rings)

Type	Kva.	Freq.	Kv. rated	Amperes rated	R. p. m.	Ω_N	X_d	X_d''	X_2	X_0
Condenser	1,000	60	2.3	252	900	5.27	1.60	0.180	0.160	
Condenser	1,250	60	.48	1500	1200	.185	1.90	0.23	0.22	
Condenser	5,000	60	12.47	232	900	31.0	1.70	0.27	0.27	0.044
Condenser	7,500	60	4.8	901	720	3.08	1.75	0.24	0.23	0.120
Condenser	7,500	60	4.0	1085	900	2.13	1.45	0.21	0.190	0.030
Condenser	15,000	60	11.95	725	900	9.52	1.55	0.20	0.190	0.031
Condenser	30,000	60	13.6	1275	720	6.17	1.70	0.23	0.20	0.110
Condenser	30,000	60	5.0	3465	720	.832	1.70	0.20	0.180	0.072
Motor	30,000	50	11.50	1505	600	4.41	.78	0.130	0.120	0.030
W. W. Gen.	3,000	50	6.6	263	750	14.5	1.60	0.165	0.160	0.036
W. W. Gen.	7,000	60	6.6	612	450	6.24	.97	0.26	0.25	0.145
W. W. Gen.	22,500	60	12.5	1040	300	6.95	1.20	0.29	0.28	0.155

*Time constants are in seconds, impedances are per unit values.

(a) X_d is from no-load and short-circuit saturation curves; X_2 from sustained line-to-line short circuit; X_d'' and X_0 from locked tests at rated current.

TABLE VIII(b)

Salient-Pole Machines without Dampers

Type	Kva.	Freq.	Kv. rated	Amperes rated	R. p. m.	Ω_N	X_d	X_d'(c)	X_2	X_0
Motor	730	60	2.3	183	1200	7.25	1.30	0.30	0.45	
W. W. Gen.	750	25	6.6	65.6	187.5	58.1	1.20	0.41	0.62	
W. W. Gen.	2,330	50	6.6	204	125	18.7	1.15	0.45	0.65	0.24
W. W. Gen.	4,250	60	2.3	1066	600	1.25	1.35	0.37	0.62	
W. W. Gen.	7,000	50	6.6	612	94	6.22	1.15	0.44	0.61	0.24
W. W. Gen.	13,750	60	6.6	1200	90	3.17	1.10	0.43	0.58	0.25
Gen.	187	60	.24	450	200	.308	.94	0.41	0.55	
Gen.	30,000	60	11.5	1500	600	4.42	1.15	0.33	0.58	0.093

(b) X_d is from no-load and short-circuit saturation curves; X_2 from sustained line-to-line short-circuit; X_d' and X_0 from locked tests at rated current.

(c) This value of X_d', times 0.88, gives (approx.) the saturated value of X_d'.

TABLE IX—TYPICAL CONSTANTS OF THREE-PHASE SYNCHRONOUS MACHINES

Reactances are per unit values, time constants are in seconds. Values below the lines give a range of values, while those above give an average value

	X_d	X_q	X_d'	X_d''	X_2	X_0*	T_{do}'	T_d'	T_d''†	T_a
2-pole turbine generators	1.10 .95–1.45	1.07 .92–1.42	0.15 .12–.21	0.09 .07–.14	(= X_d'')	.01 – .08	4.4 2.8–6.2	0.6 .35–.90	0.035 .02–.05	0.09 .04–.15
4-pole turbine generators	1.10 1.00–1.45	1.08 .97–1.42	0.23 .20–0.28	0.14 .12–.17	(= X_d'')	.015 – .14	6.2 4.0–9.2	1.3 .8–1.8	0.035 .02–.05	0.2 .15–.35
Salient-pole gen. and motors (with dampers)	1.15 .60–1.45	0.75 .40–1.00	0.37 .20–.50	0.24 .13–.35	0.24 .13–.35	.02 – .20	5.6 1.5–9.5	1.8 .5–3.3	0.035 .01–.05	0.15 .03–.25
Salient-pole gen. (without dampers)	1.15 .60–1.45	0.75 .40–.95	0.35 .20–.45	(= X_d')	0.55 .30–.70	.04 – .25	6.6 3.0–10.5	2.0 1.0–3.3		0.30 .1–.5
Condensers	1.80 1.50–2.20	1.15 .95–1.40	.40 .30–.60	.25 .18–.38	.24 .17–.37	.02 – .15	9.0 6.0–11.5	2.0 1.2–2.8	0.035 .02–.05	0.17 .1–.3

*X_0 varies so critically with armature winding pitch that an average value can hardly be given. Variation is from about 0.1 to 0.7 of X_d''.

†For single-phase machines (or three-phase machines designed for single-phase operation), T_d'' may have much higher values than listed.

Knowing the terminal voltage, load current and power factor, and δ, X_q (saturated value) is readily computed from equation (12). δ can be measured by means of a small auxiliary a-c. generator mounted on the shaft of the machine. This measurement has been described in certain stability studies.[11,12]

The equation expressing δ as a function of the variables listed above is, for the same case of a generator supplying a lagging power-factor load,

$$\delta = \tan^{-1} \frac{I X_q \cos \phi}{E_t + I X_q \sin \phi} \qquad (13)$$

Equations (12) and (13) apply not only to a generator supplying a lagging power-factor load, but also to a motor operating at a leading power factor; for the two converse cases, the sign of the second term in the denominator changes in both equations.

Appendix II

QUADRATURE-AXIS TRANSIENT REACTANCE X_q' (SATURATED VALUE)

To obtain the saturated value of X_q' by the method described, the slip test is made with rated current circulated which puts it at a disadvantage for turbine generators since this means a source of three-phase power of the same order of magnitude as the machine rating. With rated current flowing and the rotor magnetized in the quadrature axis, a dead three-phase short circuit is applied. An oscillogram of short-circuit current in all three phases is analyzed in the manner described (See Figs. 9A and 9B) for the determination of X_d'.

I = armature current just previous to short circuit (= rated value).

I' = initial symmetrical short-circuit current *neglecting* the rapidly decaying (initial) portion of the wave.

E = applied voltage (line-to-neutral value) just previous to short circuit.

The transient internal voltage previous to short circuit is

$$E' = I\,(X_q - X_q') \qquad (14)$$

but

$$I' = \frac{E'}{X_q'} \qquad (15)$$

hence

$$E' = I' X_q' = I\,(X_q - X_q')$$

whence

$$X_q' = \frac{I X_q}{I + I'}$$

but

$$I X_q = E \qquad (16)$$

therefore

$$X_q' = \frac{E}{I + I'} \qquad (17)$$

NOTE: Strictly speaking, the values of X_q' before and after the short circuit are different; to account for this difference it is necessary to first determine, at the same current, the low-current value of X_q' as in Appendix III and to use this value in computing E', then to compute the saturated value of X_q' from equation (15).

Appendix III

QUADRATURE-AXIS TRANSIENT REACTANCE X_q' (LOW-CURRENT VALUE)

This may be determined by a modification of the slip test; with the rotor magnetized in the quadrature axis, the applied voltage is suddenly disconnected, and terminal voltage recorded by oscillograph. Terminal voltage in Fig. 26 is extrapolated to zero time, *neglecting the rapidly decaying portion*, by the aid of a semi-log plot in Fig. 27.

E' = this (extrapolated) initial value (line-to-neutral).

E = terminal voltage (line-to-neutral) just previous to the removal of applied voltage.

I = armature current just previous to the removal of the applied voltage.

Then

$$E - E' = I\,X_q'$$

or

$$X_q' = \frac{E - E'}{I} \qquad (18)$$

NOTE: When applied voltage is disconnected, the three currents will be opened sequentially thus making zero time, the time at which the extrapolated voltage is to be measured, an indefinite item. The current in one line is first interrupted, then the current in the other two lines is interrupted (simultaneously in these two). There is very little difference, however, between the extrapolated values of voltage at these two instants, hence this matter of defining zero time has no practical importance.

Appendix IV

QUADRATURE-AXIS SUBTRANSIENT REACTANCE X_q'' (SATURATED VALUE)

This may be obtained from the same test used to determine the saturated value of X_q' (Appendix II). Following the same procedure, the *total* symmetrical current is extrapolated to zero time to give the initial symmetrical subtransient current; extrapolation is accomplished as in the analysis for determining X_d'' (Figs. 7, 8, and 9), being based on the maximum possible asymmetrical component (initial value). Let

I'' = initial symmetrical short-circuit current
E = applied voltage (line-to-neutral) just previous to short circuit
I = armature current just previous to short circuit (= rated value)

The subtransient internal voltage previous to short circuit is

$$E'' = I\,(X_q - X_q'') \qquad (19)$$

but

$$I'' = \frac{E''}{X_q''} \qquad (20)$$

hence

$$E'' = I''\,X_q'' = I\,(X_q - X_q'')$$

whence

$$X_q'' = \frac{I\,X_q}{I + I''} \qquad (21)$$

but

$$I\,X_q = E$$

therefore

$$X_q'' = \frac{E}{I + I''} \qquad (22)$$

The same note given in Appendix II applies here; that is, the difference in values of X_q'' before and after the short circuit may be accounted for by first measuring the low-current value by another test, similar to that in Appendix III.

Appendix V

X_0 FROM SUSTAINED DOUBLE LINE-TO-NEUTRAL SHORT CIRCUIT

By the method of symmetrical components, it can readily be shown[13,14] that with a double line-to-neutral short circuit on phases *b* and *c* at the machine terminals (See Fig. 12), the voltage on the open phase is

$$\check{E}_a = \frac{3\,\check{Z}_0\,\check{Z}_2\,\check{e}}{\check{Z}_0\,\check{Z}_1 + \check{Z}_0\,\check{Z}_2 + \check{Z}_1\,\check{Z}_2}$$

and that the neutral current is

$$\check{I}_n = 3\,\check{I}_0$$

$$= \frac{-\,3\,\check{e}\,\check{Z}_2}{\check{Z}_0\,\check{Z}_1 + \check{Z}_0\,\check{Z}_2 + \check{Z}_1\,\check{Z}_2}$$

Where

$\check{e}$ = generated (line-to-neutral) voltage of phase *a*.
$\check{I}_0$ = zero-sequence current
$\check{Z}_0, \check{Z}_1, \check{Z}_2$ = sequence impedances of the machine.

Dividing $\check{E}_a$ by $\check{I}_n$ gives

$$\check{Z}_0 = -\,\frac{\check{E}_a}{\check{I}_n} \qquad (3)$$

Appendix VI

NEGATIVE-SEQUENCE REACTANCE X_2

It has been shown[5] that the ratio of voltage to current, both fundamental negative-sequence quantities, depends upon whether (1) the current or (2) the voltage, is maintained fundamental. Condition (1) is approached with large external reactance, and (2) is approached for double line-to-neutral and line-to-line short circuits. In systems where generators are connected to delta-wye transformers they carry no zero-sequence current for line faults, and in view of this and other considerations, more importance is placed on the value of X_2 for line-to-line generator short circuits than for double line-to-neutral short circuits. For condition (1) above, $X_2 = (1/2)\,(X_d'' + X_q'')$ and for a line-to-line short circuit, $X_2 = \sqrt{X_d''\,X_q''}$; the difference between these two values will be computed for a case where X_d'' and X_q'' are quite different, as for a salient-pole machine without dampers where $X_d'' = X_d' = 0.35$ and $X_q'' = X_q = 0.75$. For this case

$$\frac{X_d'' + X_q''}{2} = 0.55 \text{ and } \sqrt{X_d''\,X_q''} = 0.51$$

from which it can be concluded that for most practical purposes, the arithmetical average of X_d'' and X_q'' (in this case 0.55) may be taken as the value of X_2.

Appendix VII

Negative-Sequence Impedance from Sustained Line-to-Line Short Circuit

Referring to Fig. 13, it has been shown[13,14] that for a line-to-line short circuit on phases b and c, the short-circuit current

$$\check{I}_b = -j \frac{\sqrt{3}\,\check{e}}{\check{Z}_1 + \check{Z}_2}$$

and the line-to-line voltage

$$\check{E}_{ab} = \frac{3\,\check{e}\,\check{Z}_2}{\check{Z}_1 + \check{Z}_2}.$$

Where $\check{e}$ = generated voltage of phase a.
$\check{Z}_1, \check{Z}_2$ = sequence impedances of machine.

From which

$$\frac{\check{E}_{ab}}{\check{I}_b} = \frac{\sqrt{3}\,\check{Z}_2}{-j}$$

hence

$$\check{Z}_2 = \frac{-j}{\sqrt{3}} \cdot \frac{\check{E}_{ab}}{\check{I}_b} \tag{5}$$

Appendix VIII

X_d' and T_d' as Regards Saturation Effects

Since transient reactance is based on an initial value of current (neglecting the initial rapidly decaying portion), the use of different values of X_d' for various degrees of saturation is an accurate treatment. Since time constants define decrement (or increment) only if it is exponential, and since saturation causes decrement to be other than exponential, the use of time constants for short-circuit conditions is not an exact treatment. However, assuming that the most important portion of a decrement is that during the period when the value is relatively large, the approximation of employing a saturated time constant for saturated conditions gives reasonably accurate results.

In order to study the relation between saturated and rated current values of X_d', tests made under various degrees of saturation were analyzed. It was found that in general, the reduction in X_d' could be accounted for in two ways; first, by a factor equal to the ratio of (field amperes at rated voltage on the air gap line) to (field amperes at rated voltage no load)—which ratio is simply the reciprocal of the product of X_d and the short-circuit ratio; second, by an empirical factor = 0.88, based on test results. However, it was also found that the relation between the saturated and unsaturated values of T_d' was better accounted for by the empirical factor 0.88 than by the first factor, and it is on this basis that the factor 0.88 has been adopted.

Three-phase short circuits were made at low voltages as well as at rated voltage, and analysis of results has lead to the conclusion that one of the important causes of reduction of X_d' and T_d' is due, in salient-pole machines, to saturation of the iron in the pole tips. Thus it would be expected that under short-circuit conditions the values of X_d' and T_d' depend not only on armature short-circuit current, but also on the voltage and field current existing before short circuit.

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Discussion

P. L. Alger: This paper presents a thorough summary of test methods of reactance determination, which will be very useful for both designers and operators. The methods of determining zero phase and negative phase sequence reactances from measurement of voltages on the open phases under partial short circuit are particularly valuable.

The paper establishes satisfactory methods for determining the unsaturated values of all the important reactances, but only suggests the determination of saturated reactance by full voltage short-circuit tests. I do not believe that full voltage short circuits are desirable for regular use in factory tests, as they require undue expense and special safety precautions for holding the machine stator in place against the short-circuit forces. Furthermore, the only record of such tests is oscillographic, and the accuracy obtainable from oscillographic films is not of a high order, so that at best only approximate values of reactance can be so obtained.

For practical purposes, the operator usually requires only saturated values of the transient and subtransient reactances, though unsaturated values may be useful in calculations such as machine oscillation and stability determinations. These are primarily used for determining fault currents and relay settings.

The synchronous reactances are chiefly useful in determining steady state torque angle relations and sustained short-circuit currents, and for these purposes the unsaturated values are desired.

I believe the best way to determine the saturated transient and subtransient reactances is to apply saturation factors to the test values of unsaturated reactance, as mentioned in my discussion of Mr. Kilgore's paper on page 1214. The errors introduced by the use of such factors in my opinion should not be of greater magnitude than allowable with the accuracy requirements for practical use at the present time.

Sherwin H. Wright: The method of evaluating saturated values of synchronous machine constants by applying saturation factors to measured unsaturated values, as commented upon by Mr. Alger, may well be amplified and extended in use in the future. Limited application of this method appears in the paper, wherein the saturation factor for both transient reactance (X_d') and short-circuit time constant (T_d') is given as 0.88; thus in Table VIII (salient pole machines without dampers) the value of transient reactance as measured at rated current by a locked rotor test, when multiplied by 0.88, gives the saturated value. In the case of turbine-generators, transient reactance cannot be determined from this same locked rotor test, but if a sudden three-phase short circuit is made at half voltage and the value of transient reactance thus found is multiplied by 0.88, the result is approximately the saturated value of transient reactance.

Extension of this general method can be accomplished only after considerable additional test analysis is carried out, such as will lead up to a better understanding of the mechanism of saturation effects in machines under short circuit. However, to reach such a state we must first know the actual saturated values of machine constants, and it is for this reason that, in the paper, emphasis has been placed on the determination of certain of the constants by full voltage short circuit.

An A-C. Supervisory Control System

BY OTHMAR K. MARTI[1]

Member, A. I. E. E.

As a result of the rapid extension of electric power systems and the progress of electrification of railroads, the control engineer has been called on to provide solutions for increasingly intricate control operations. Coordination between those operations led to their concentration into the hands of a single operator or dispatcher, and the adoption of automatic and of remotely controlled substations. In order to be able to control equipment located at appreciable distances it was necessary to reduce to a minimum the number of wires required for transmitting a large number of different signals, which led to the adoption of different designs of supervisory control. At the time of the adoption of those systems it was felt that only a d-c. system, operating with a battery as current supply, would be a reliable solution, as a system directly supplied by the power lines to be controlled would be affected by disturbances in these lines, at times when supervision is most urgently required.

SIMPLIFIED DIAGRAM OF SYSTEM

Alternating current was, however, chosen for operating the present system, whose principle of operation is illustrated diagrammatically in Fig. 1. This figure shows a controlling station *I* and a controlled station *II*, which are connected by five wires. The a-c. supply may be located in the controlling station, or in any one of several controlled substations, and can be made independent of all disturbances by using a fractional horsepower motor-generator set, supplied from the station battery which is usually present. In most instances, however, it will be found possible to dispense with the battery and motor-generator set without sacrificing reliability. Such a possibility exists, for instance, if the house supply of a generating station can be made available for energizing the supervisory control system, as this supply is not affected by any disturbances to the high-tension lines feeding the controlled substations. Another alternative resides in supplying power to the supervisory control system from the power lines at the controlling station and at each controlled substation, if these latter are fed from the same power system. In this case the supervisory system will be dead only if the power fails simultaneously at all feeding points. Disturbances in the low-voltage side of the controlled substations cannot affect the supervisory system.

In networks with a large number of internal connections it may even be felt that the presence of normal voltage on the substation bus can be depended on at all times, so that the stations can be supplied independently of each other, thereby eliminating the necessity for the two supply line wires shown on Fig. 1, which can then be replaced by a single return wire. In some cases an additional degree of safety can be obtained if a supervisory control system of this kind is supplied from one high-voltage network while controlling another independent network. Each individual case will show the best current supply to be used.

SYNCHRONOUS SELECTORS

The system described herein was developed with a view to great reliability. It uses equipment of a very sturdy type, which has been used in the past in relay applications, and is little apt to be disturbed by even severe inductive interference, and can further be protected from disturbances by the insertion of insulating transformers into the lines. It is of the synchronous selector type, each station comprising one selector, started from its rest position when an operation is to be performed, and returned to this position after the operation has been completed. Depending on the complexity of the operations to be performed, and their number, these selectors are provided with a variable number of rows of contacts which are connected to slip rings by means of rotating brushes carried by an arm, and are made with a variable number of operating points.

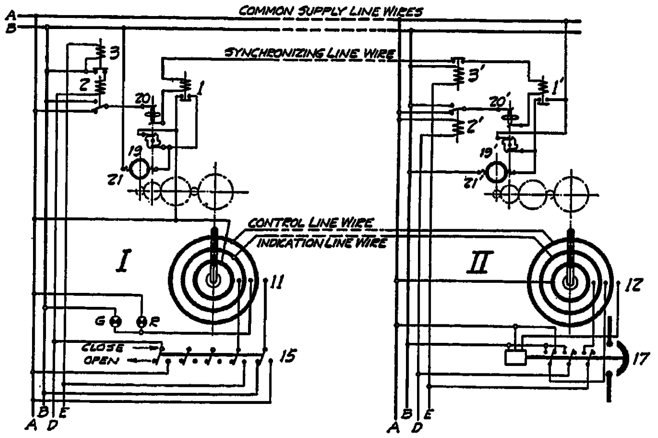

FIG. 1—SIMPLIFIED WIRING DIAGRAM

I	Controlling station
II	Controlled station
1, 1'	Selector relays
2, 2'	Starting relays
3, 3'	Stopping relays
11	Controlling station selector
12	Controlled station selector
15	Control switch
17	Circuit Breaker
19, 19', 20, 20'	Auxiliary contacts
21, 21'	Selector motors

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[1] Chief Engineer, American Brown Boveri Co., Inc., Camden, N. J.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

Fig. 2 shows a selector having 23 operating positions, but selectors have been made with as many as 67 operating positions. These selectors are driven by a motor which is the heart of the whole installation. This motor is shown in Figs. 3 and 4. Its main component parts are a permanent magnet 1 and a wound armature 2 free to oscillate in the air gap of the magnet. The armature spindle carries a torsion spring fastened to the frame, and so dimensioned that it gives to the armature a natural oscillation frequency equal to the a-c. supply frequency. When alternating current is applied to the armature through flexible leads, the armature therefore oscillates at the system frequency, and, in order to utilize this oscillatory motion, the armature is connected to the selector arm through a ratchet mechanism and a set of gears. This motor, not possessing any contacts, slip rings, or commutator, is particularly reliable, and it has proved its worth in many years of service in central station and substation relays. The selector spindle carries a gear wheel 5 having as many teeth as operating positions are required, plus one for the rest position. This gear wheel is driven by a pinion 4 having only 2 teeth, driven through gears by the motor. The substantially uniform rotation given by the motor to pinion 4 is transmitted to gear 5 as a step-by-step motion, allowing the brushes of the selector to rest on the contacts for a comparatively long time while a much shorter time is spent in moving them from one contact to the next. One of the intermediate gear spindles carries sets of auxiliary contacts 3, the purpose of which will appear from a description of the operation of the system, and makes one-quarter turn each time the selector moves by one step. It has been found that an operating time of ⅓ to ½ sec. per step permits satisfactory operation of all the relays.

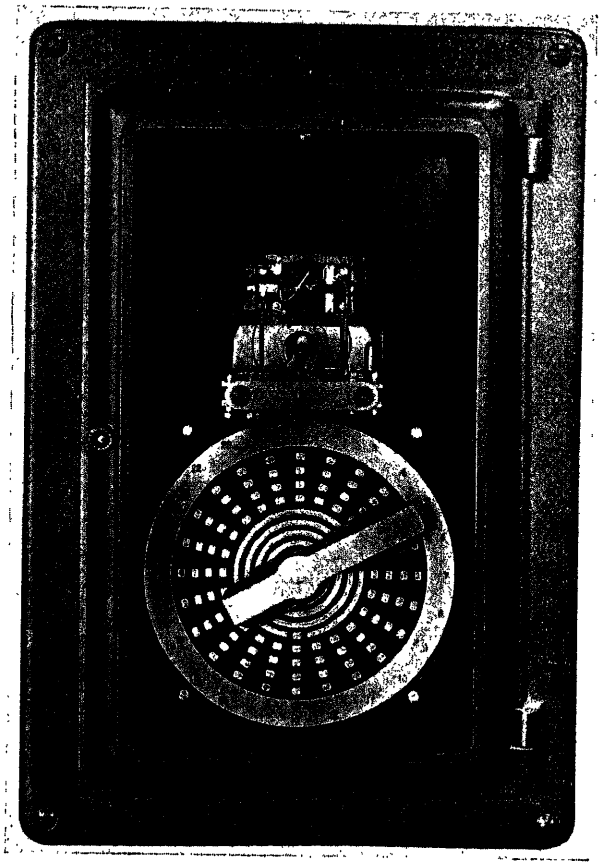

Fig. 2—Front View of Selector

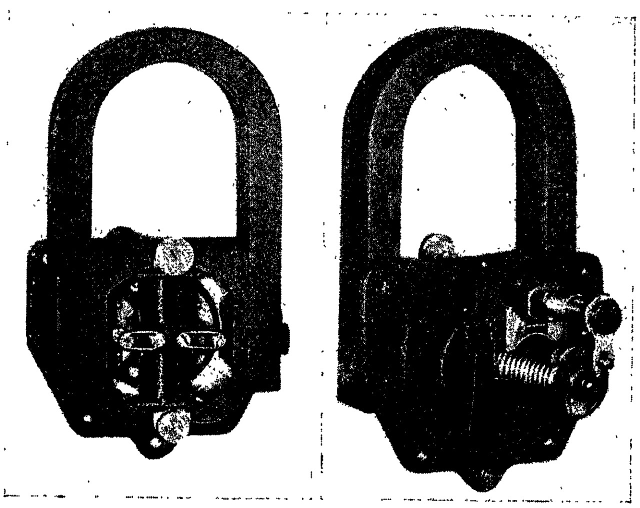

Fig. 3—Front and Rear Views of Selector Motor

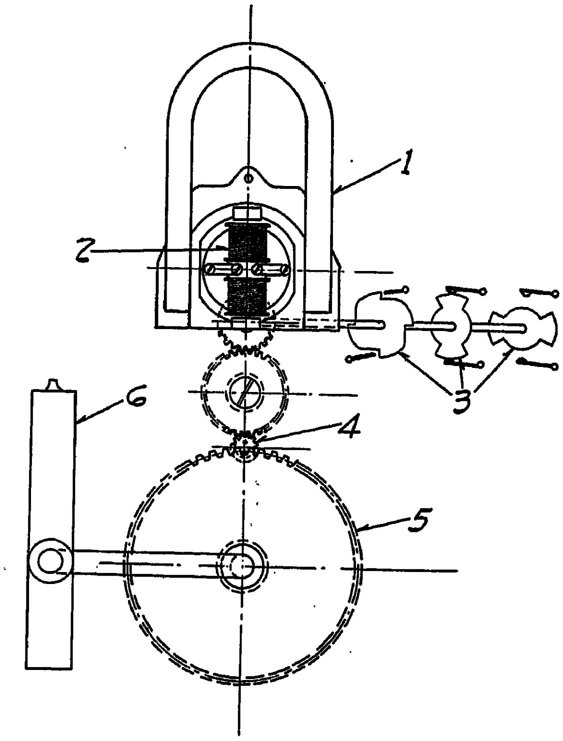

Fig. 4—Diagram of Selector Motor

1 Permanent magnet
2 Armature
3 Auxiliary contacts
4 Pinion
5 Selector gear
6 Selector arm

PRINCIPLE OF OPERATION

Fig. 5 shows the complete equipment required for the operation of selectors in two stations and, in order to give a typical example of the operations that can be performed, also shows the equipment required for the control and supervision of one circuit breaker. The principle of operation of the selectors will be understood more readily by first referring to the simplified circuits of Fig. 1. As mentioned above, the controlling station is provided with a source supplying alternating current to auxiliary bus bars, *A*, *B* and, over the supply line wires, to the controlled station, where it supplies also a set of auxiliary bus bars, *A*, *B*. Each station also possesses a starting bus *D* and a stopping bus *E* for controlling the operation of the selectors. If we assume that the selector arms are in the rest position, as shown in Fig. 1, and that it is desired to close the circuit breaker 17, the control switch 15 of the circuit breaker is moved to the "close" position. The control switch, which is illustrated in Fig. 6, is provided with a number of contacts. One of these contacts connects the starting bus *D* to bus bar *A*, thereby energizing starting relay 2. Until the starting relay is energized, the synchronizing wire line is in connection with bus bar *A* in both stations *I* and *II*, and is therefore without current. When the starting relay 2 operates, its contacts connect one end of the synchronizing line to bus bar *B*; the synchronizing line thus receives current, energizing selector relays 1 and 1′. The latter connect to the bus bars the selector motors 21, 21′, which start to rotate. This rotation is transmitted to contacts 19, 19′, which first connect the motors directly to the bus bars, to contacts 20, 20′, which open the synchronizing line and through the two-tooth pinions, to the selector arms which move to the first step. When this step is reached, contacts 20, 20′ first reclose the synchronizing line, and contacts 19, 19′ then disconnect the motors from the bus bars. Starting relay 2 still being closed, another current impulse is sent over the synchronizing line, reenergizing selector relays 1, 1′, before contacts 19, 19′ open, thereby initiating another one step motion of the selector arms through the same sequence of operations. It is apparent from the above procedure that each selector arm can leave a step only if this step has also been reached by the other selector arm, and that the motion of the selectors is obtained independently until they both again reach the following step. If one of the selectors should fail to operate while between two steps,

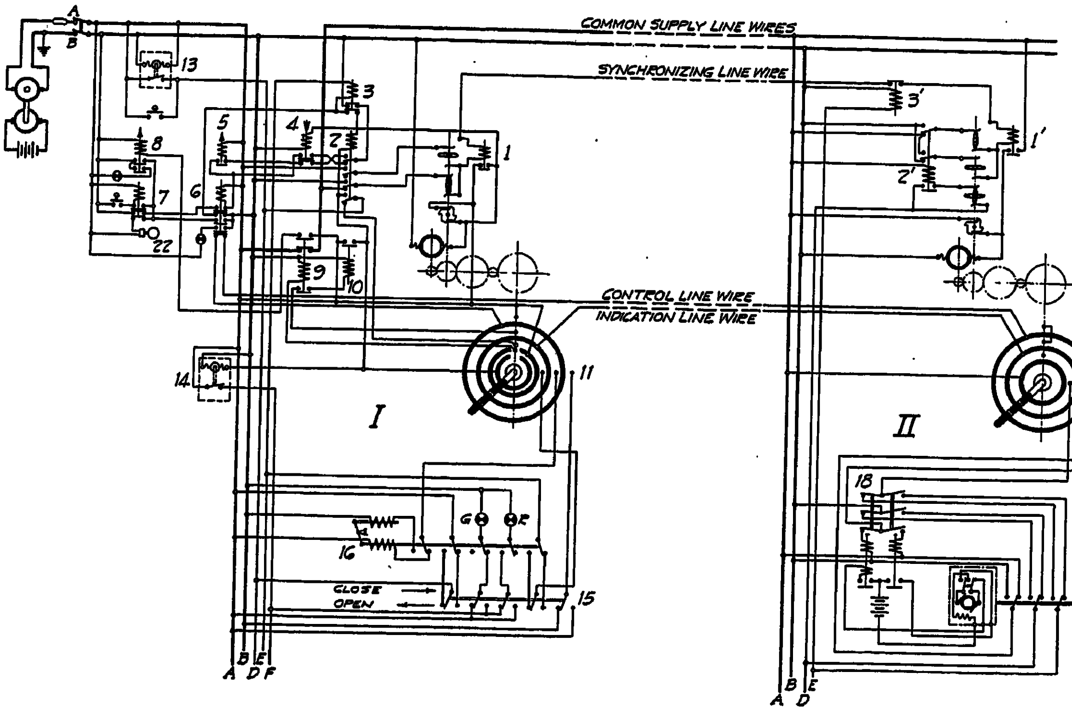

FIG. 5—WIRING DIAGRAM OF A TYPICAL INSTALLATION

I	Controlling station
II	Controlled station
1, 1′	Selector relays
2, 2′	Starting relays
3, 3′	Stopping relays
4	Auxiliary selector relay (time delay on opening)
5	Auxiliary signal relay (time delay on closing)
6	Signal relay
7	Alarm relay
8	Trouble relay (time delay on closing)
9	Auxiliary starting relay
10	Synchronism checking relay
11	Controlling station selector
12	Controlled station selector
13	Time switch
14	Blinking relay
15	Control switch
16	Indicating relay
17	Circuit breaker
18	Control relay
19, 20, 19′, 20′	Auxiliary contacts
21, 21′	Selector motors
22	Alarm device

the other selector would be unable to proceed. In normal operation, the two selector arms proceed without stopping over the successive steps until they both reach the step assigned for the control of circuit breaker 17.

One of the brushes of selector 11 then connects bus bar *A* through the control switch to the stopping bus *E*. Stopping relay 3 is then energized and opens the circuit of starting relay 2, which reconnects the synchronizing line to bus bar *A* as when the system was at rest. The selector relays 1 and 1′ therefore are deenergized and the selector arms remain at standstill. Another brush of selector 11 then sends the control impulse over the control line wire and over selector 12 to the control circuit of the circuit breaker, causing it to close. The circuit breaker auxiliary contacts then send an indicating signal back over the indicating line wire.

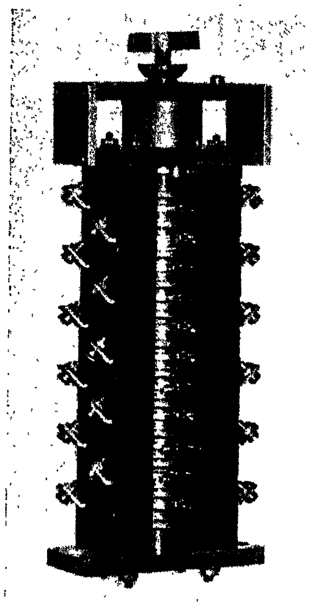

Fig. 6—Control Switch

The above operation can be followed in somewhat more detail on Fig. 5, on which the selector arms were displaced from their rest (vertical) position for the sake of clearness. When the control switch 15 is moved to the "close" position, it connects bus bar *A* to the starting bus *D* and, through the selector brush, energizes auxiliary starting relay 9. The latter energizes the synchronism checking relay 10, which can close only if both selector arms are in the rest position. If selector 12 happens to be in any other position, the auxiliary starting relay 9 will remain energized and it will operate the time delay trouble relay 8; at the same time, it opens supply line wire *A*, so as to avoid the transmission of erroneous indications back from station 11. Normally the selectors are in the rest position and permit the synchronism checking relay to close, thereby energizing the starting relay 2, which initiates a rotation of the selector arms as described above. Relay 9 is then deenergized by selector 11 and opens the circuit of trouble relay 8.

As a third protection against the loss of synchronism, the auxiliary contacts of the selectors reverse the polarity of the synchronizing line at each step, so that if one of the selector arms happened to jam on one step, the other selector arm would be unable to proceed further than the next step. Once the selector arms have started to rotate, the starting relay remains energized through the inside slip ring of selector 11. When the circuit breaker has been closed, as explained above, and the return indication transmitted, the stopping relay 3 is deenergized by the indicating relay 16, so that both selector arms again proceed until they reach their rest positions; the starting relay is then deenergized by selector 11 and the system comes to rest. When the circuit breaker trips automatically, it energizes starting relay 2′, which sets the two selectors in motion, in the same manner as when starting relay 2 is energized. When selector relay 1 closes its contacts, the auxiliary selector relay 4 is energized, and since the starting relay 2 is not energized, a circuit is completed for energizing the signal relay 6, which lights a signal lamp, and energizes an alarm device 22, such as a bell or a horn. The operator is thereby notified of the tripping of the circuit breaker, and he disconnects the horn by means of the alarm relay 7. The two selectors are stopped by means of

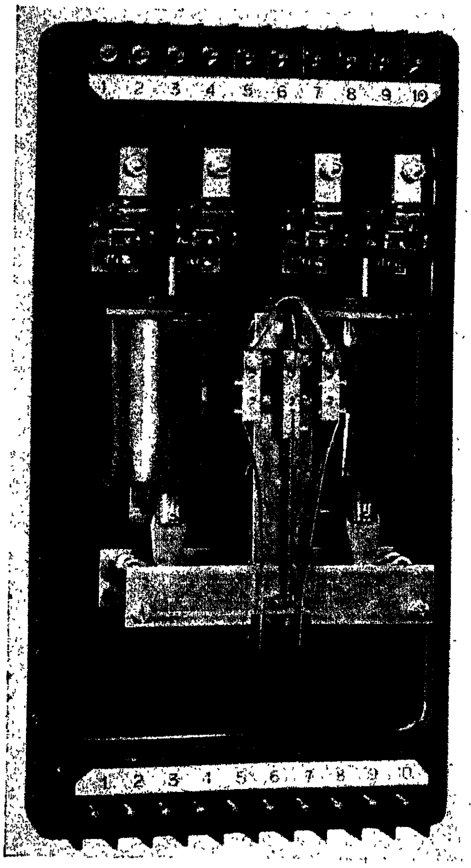

Fig. 7—Control Relay

stopping relay 3′, and the return indication is then transmitted over the indicating line wire. The operator then moves the control switch of the circuit breaker to the "open" position, thereby reversing control relay 18 which permits the selectors to return to the rest position. If we now assume that the circuit breaker trips while the selectors are rotating for the purpose of transmitting a control impulse, it will again energize starting relay 2′, but as starting relay 2 is also energized, the two ends of the synchronizing line will be connected to the same bus bar, and both selectors will stop. At the same time, auxiliary indicating relay 5 will be energized, thereby again energizing the signal relay 6, and sounding the alarm. The operator must then cancel the operation he had started by replacing his control switch in the initial position and moving the control switch of the circuit breaker which has tripped. If several breakers have tripped, this operation would be repeated for each one, before the operator can transmit any control impulses.

When the operator wishes to perform a control operation, he is thus positively assured that, while that operation is being completed, the equipment which this operation does not affect will still be in the condition shown by the lights on his switchboard. This condition can only be the result of operations either initiated or acknowledged by himself by means of his control switches. In this manner the danger of the operator becoming confused and performing undesired operations is reduced to a minimum.

An interesting feature of the controlling station is the blinking relay 14. This relay comprises a motor, similar to the selector motors, which rapidly makes and breaks connection between bus bar A and a blinking bus F, and operates only when selector 11 is not in its rest position. A lamp connected between bus bars B and F will then blink instead of giving a steady light. When the operator wants to close breaker 17 and moves control switch 15, the green lamp starts to blink until the circuit breaker has closed, after which the indication relay 16 extinguishes the green lamp and lights the red lamp. Conversely, when the circuit breaker trips automatically, alarm 22 sounds and the green lamp will blink until the operator moves the control switch to the "open" position, when the green lamp becomes steady. This combination of an alarm signal with a blinking light is most effective in bringing the operator's attention to whichever piece of apparatus has performed automatically. In addition, in order to avoid the automatic reclosing of the circuit breaker when it has tripped, it is provided with a control relay 18, shown in Fig. 7, through which the circuit breaker can be reclosed only by first moving the control switch to the "open" position, and then back into the "close" position.

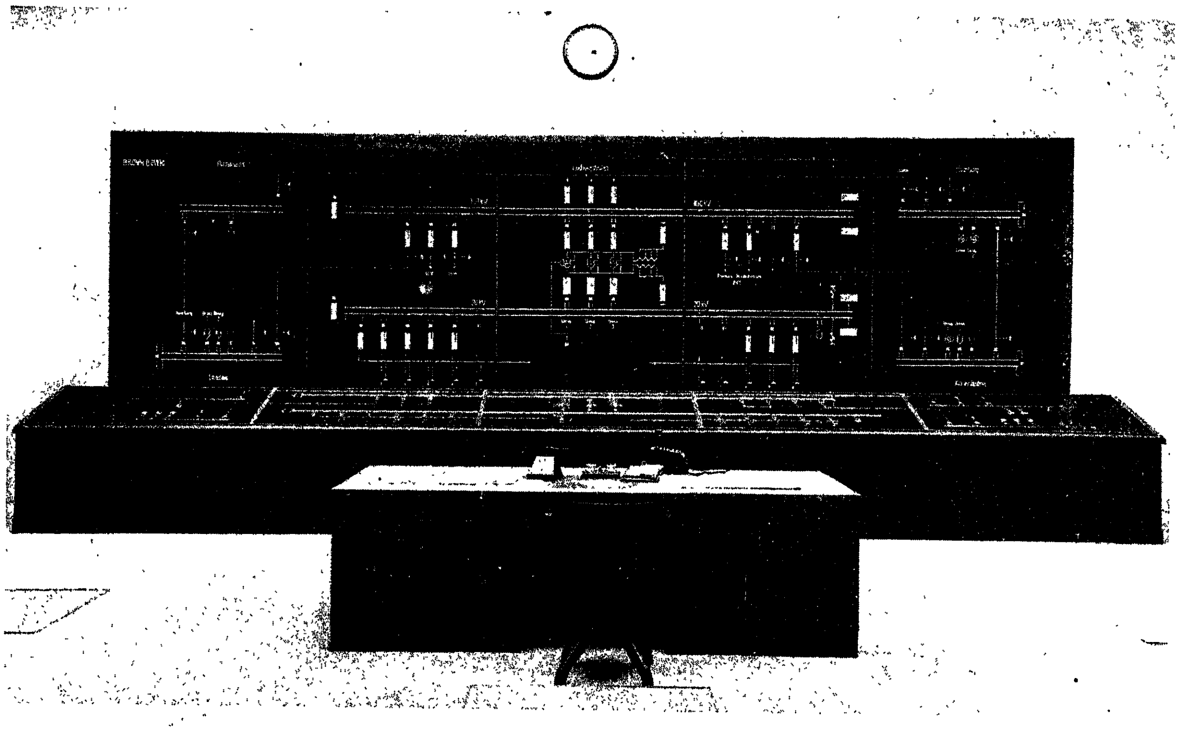
FIG. 8—VIEW OF SWITCHBOARD AND CONTROL DESK

Analogous circuits can be provided for other control and supervision operations such as, for instance, reading of meter indications, automatic position indication of manually operated disconnecting switches, alarm indications to warn of excessive temperatures or other disturbances in the substation, etc.

OPERATING DETAILS

It may happen, in some instances, that the supervisory system remains idle for hours or even days. In order to give a periodic check of the condition on the system, station *I* is provided with a time switch 13 which periodically sends an impulse to starting relay 2. This impulse starts both selector arms, which pass over every control step and come back to their rest position, where they automatically stop. Thus every step is checked, and it can therefore be ascertained that no change has occurred in the power system since the last control or supervisory operation. This check operation can also be initiated by means of a push button.

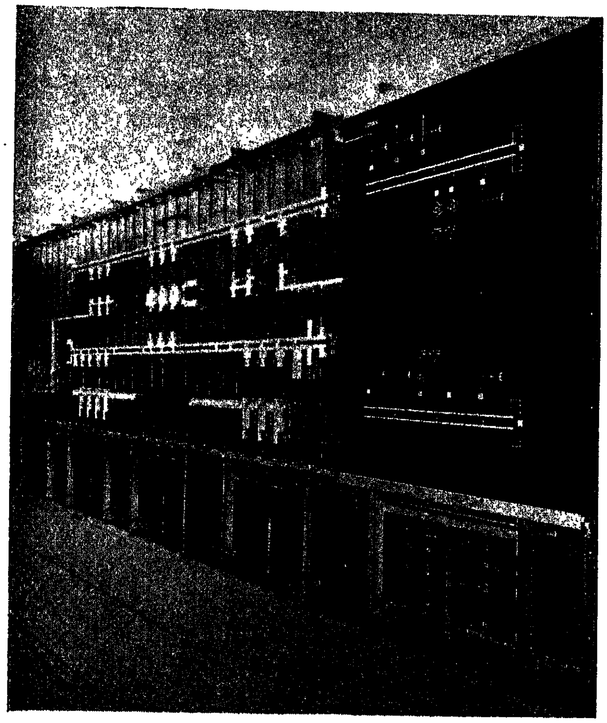

Fig. 9—View of Partially Assembled Luminous Switchboard

It will be noted that, when the operator needs to perform at one time a number of control operations which can be transmitted without any particular sequence, he can move all the corresponding control switches to their new positions, and the selector arms will transmit the control and signal impulses in the order of the corresponding contacts of the selectors.

The installation described above can be considered as typical, but can easily be modified to meet local conditions, as the principle of its operation permits a great amount of flexibility. A single selector in the controlling station can be used for controlling a number of selectors in outlying stations, the controlling selector then being provided with a number of steps equal in number to the total number of steps of the controlled selectors.

The control switches, selectors, control lamps, and various relays, can be mounted in different ways on switchboards or control desks. Fig. 8 shows a disposition applicable both to manual and to supervisory control, which enables the operator to visualize at all times the condition of the system which he is controlling. In this figure the control switches are installed on a switch desk in front of the switchboard, the handles of the control switches being part of a set of dummy buses, so that the positions of all circuit breakers can be visualized. The switchboard, as may be seen in more detail in Fig. 9, is built of sheets of glass, covered by an opaque paint leaving transparencies which form a diagram of the buses and lines duplicating the dummy set of buses on the switch desk. The indicating lamps are disposed behind the switchboard, so as to show, in proper colors, the positions of the circuit breakers. Additional indicating lamps provide for the indication of whether or not the buses and lines are energized, for which purpose they are controlled by suitable relays connected to the circuit breaker controlling circuits. Additional transparencies provided in the lines can be used for indicating the readings of ammeters, voltmeters, or other instruments. Each of these transparencies discloses a meter box having a ground glass front graduated so as to provide a scale, on which the readings are given by the shadow of the moving element of one or of several instruments. In this manner each meter is located so that it is immediately apparent to which circuit the reading refers. Fig. 10 shows a typical arrangement of three feeder ammeters with a three-phase bus voltmeter with suppressed scale.

This method of enabling the operator to visualize at a glance the condition of the network and the changes occurring therein, the position of the switching equipment, and the location of meter readings, greatly facilitates the supervisory operations, and reduces the chances of wrong operations being performed. In addition, the equipment is of a type with which the operators and maintenance crews are familiar, so that no special training is required for the personnel. These two advantages, with the flexibility and reliability of the equipment, should make this system of particular interest to operating engineers.

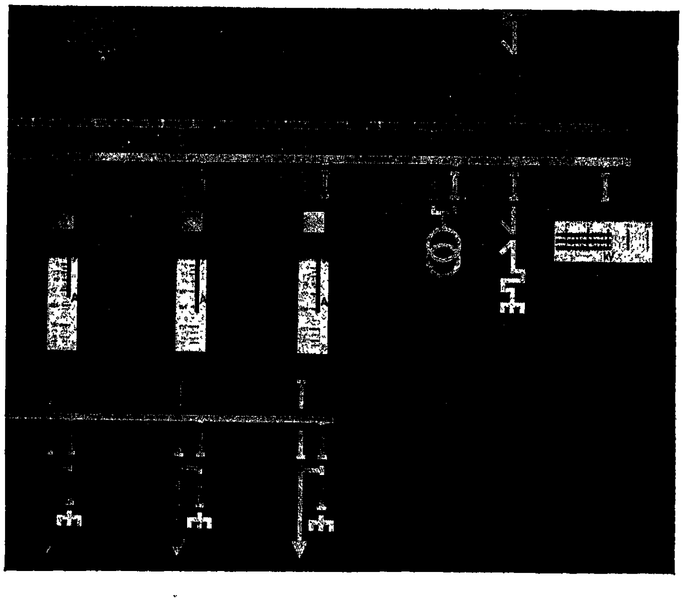

Fig. 10—Detail of Luminous Switchboard

Supervisory Control for A-C. Electrified Railroads

BY C. P. WEST[1] and H. C. GRIFFITH[2]
Member, A. I. E. E. Non-member

THE Pennsylvania Railroad in its electrification in and around Philadelphia has made use of two installations of supervisory control for the remote operation of high-voltage a-c. step-down substations. One installation is on the branch line from Philadelphia to West Chester. It centralizes the control in the signal tower at Wawa, approximately 18 miles from Philadelphia, for four separate substations along the West Chester Branch—one at Morton 10 miles from Philadelphia, one at Lenni 17½ miles from Philadelphia, one at Cheyney 22 miles from Philadelphia, and one at West Chester 27½ miles from Philadelphia. The relative locations of these substations and the control point at Wawa are shown in Fig. 1.

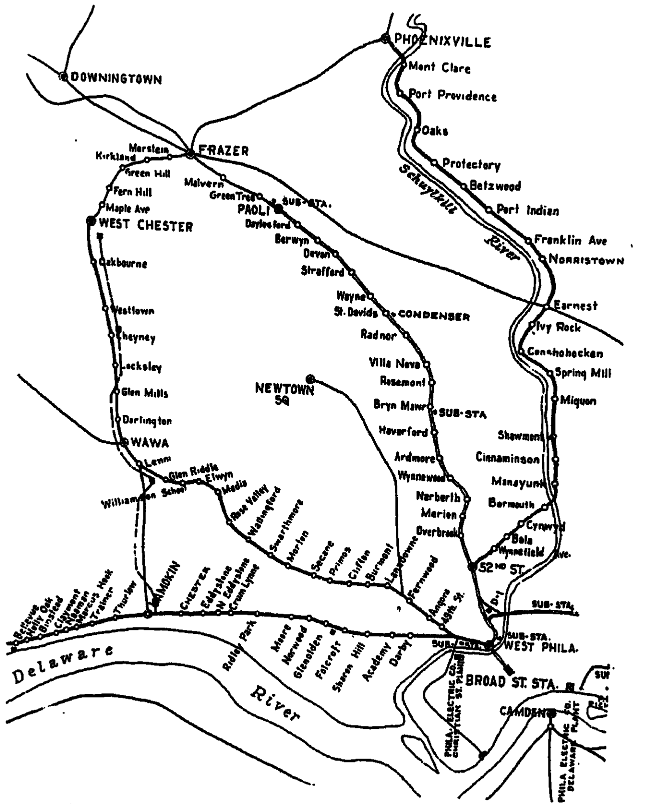

Fig. 1—Map Showing Portion of Pennsylvania Railroad Electrified Territory

The regular practise of the Pennsylvania Railroad is to install substation control in signal towers adjacent to the individual substations. This can be done in most cases, since the substation locations selected are usually adjacent to interlockings, where signal towers are also located.

On the West Chester branch, however, there is but one signal tower which is manned for the 24-hour period of each day, namely at Wawa. It is, therefore, desirable to concentrate at this point the control of the four stations mentioned above. (Fig. 2.) Supervisory control makes this possible. The operator in the tower at Wawa receives detailed instructions from the system power director at Philadelphia by telephone. This operator then performs by use of supervisory control such operating movements as are desired. In case of trouble developing along the line which involves the automatic opening of circuit breakers in any of the four substations, these indications are brought to the operator at Wawa by supervisory control. The operator in turn advises the power director by telephone of the change in the switching conditions and receives from him suitable instructions as to what movements to make.

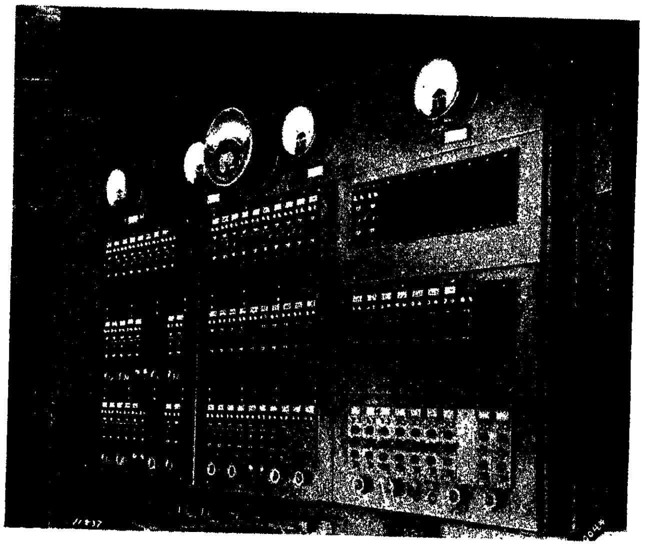

Fig. 2—Control Board—Wawa Tower

The second installation of supervisory control was installed at D-1 substation which is located at 36th Street, Philadelphia, along the main line tracks of the Pennsylvania Railroad to the west and east. (Fig. 3.) This location is directly back of the Philadelphia Zoological Gardens. At the time this substation was initially installed, it was definitely known that the only signal tower near the substation would be abandoned at

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[1] Switchboard Engineer, Westinghouse E. & M. Co., E. Pittsburgh, Pa.

[2] Asst. Elec. Engr., Pennsylvania Railroad Co., Philadelphia, Pa.

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a later date, but the location of the new tower replacing it was not known. It was, therefore, decided that the control of this substation, which is one of the key stations in the Philadelphia district, would be carried directly to the power director's headquarters adjacent to the Pennsylvania Station at West Philadelphia. This permits the power director, who is the operating department man directly in charge of the entire electrification system, to control the operation of the equipment in an outlying substation and to receive direct and prompt indications of trouble involving that station.

In addition to the customary control wires for the manipulation of apparatus, there was also installed as part of the supervisory control, on both the D-1 and the West Chester Branch, voltage wires for the direct and continuous indication at the control point of the potential on the substation 11,000-volt bus. At the time the supervisory control was built for the West Chester branch, a system known as the synchronous visual type was standard with the Westinghouse company. This equipment was installed in the spring of 1928. The power supply was obtained from 48-volt batteries located at each of the substations and at Wawa tower. Eight wires in an unshielded lead-covered telephone cable were installed between the dispatcher's office and each substation, four for operation of the supervisory equipment and four as spare wires which could be cut into the circuit by operating a push button.

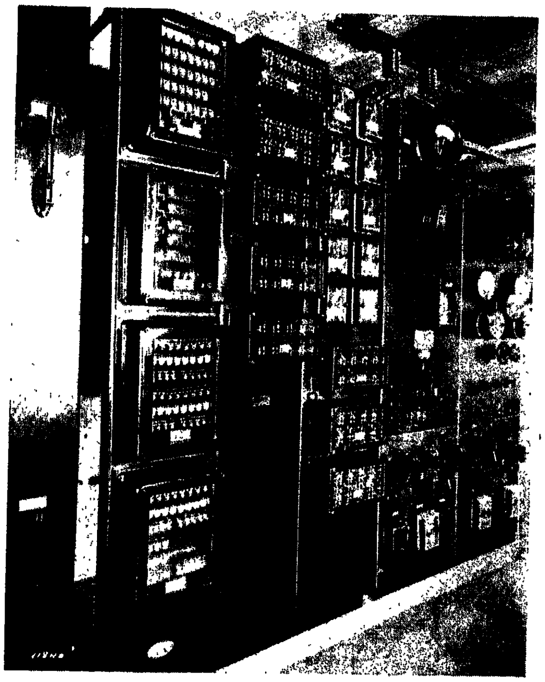

Fig. 3—Typical Supervisory Equipment Installed in Substation Control House

When the electrification was put in service in July 1928, it became apparent that, when the 11,000-volt, 25-cycle trolley circuits were fed from one end only, voltages were induced in the control wires from the substations to the dispatcher's office which interfered with the operation of the supervisory equipment. The first indication of this condition was the blowing of fuses, both in line wires and battery circuits when trolley faults occurred. Later, it was observed that when heavily loaded trolley sections were fed from one end, sufficient voltage was induced in the supervisory line wires to cause some of the relays in these circuits to chatter. Under these conditions the supervisory system was inoperative.

Before the effects of induction were fully realized, many of the supervisory failures were credited to improper adjustments, circuit design or lack of maintenance. The Westinghouse company had numerous installations of synchronous visual supervisory in operation giving excellent service. The railroad company felt that it had done its share in maintaining the equipment and yet the results were most disappointing. Tests were made in January 1930 which definitely proved that the faulty operations were caused by voltages induced in the supervisory wires by the current in the contact lines. Plans were immediately made to change the equipment so that it would not be affected by induction. The obvious method was to arrange some form of drainage circuit to remove the induced 25-cycle energy from the supervisory wires.

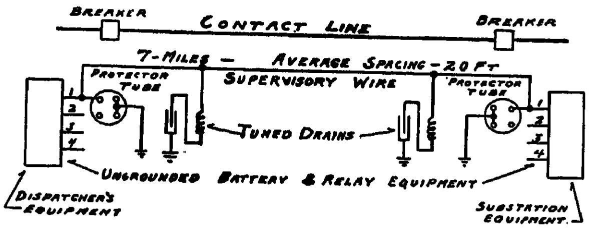

Fig. 4—One Wire of a Supervisory Control Line Between a Substation and Dispatcher's Office

A single line wire between a substation and the dispatcher's office is shown in Fig. 4.

High voltage induced in the supervisory wire will cause the protector tubes to break down. This voltage, even on load currents, was sufficient to cause the tubes to flash over and the current through them, being caused by a steady rather than transient condition would continue to flow till the tubes were destroyed. Tuned drainage circuits were connected to the supervisory wires at the substation and dispatching ends. These drains were so designed that they could carry enough current to hold the potential between the supervisory wire and ground below the flashover value of the protector tubes.

Three conditions had to be fulfilled in this design: first, the capacity connected to the line wires must not be so great as to absorb the direct current impulses for relay operation; second, the size of the drainage equipment must be held within reasonable limits; and third, the drains must have sufficient capacity to handle the maximum currents induced by full loads fed from one end of the trolley section. Investigations showed that not more than 10 microfarads could be connected from the supervisory line wires to ground without interfering with relay operation. Values above this tended to absorb the direct current impulses sent out from one station to the other or to cause incorrect relay operation by condensers discharging through coils. If the drains were to have a sufficiently low 25-cycle impedance (150 ohms) and not use over 10 microfarads of capacity, the reactor became too large to go into the space available in the dispatcher's office. These considerations resulted in discarding resonant drains as a solution to the problem.

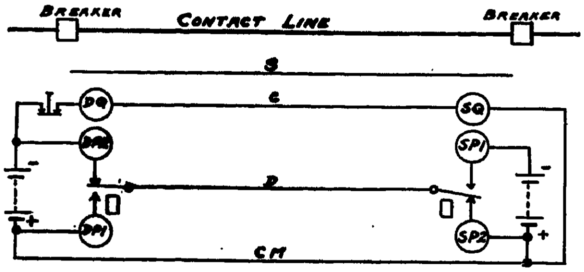

FIG. 5—SCHEMATIC LINE CIRCUITS FOR SYNCHRONOUS VISUAL TYPE SUPERVISORY CONTROL

Another common way of overcoming the effects of induction is to build a system of balance coils so arranged as to be highly reactive to the direct current impulses of the signaling circuit and to present a low impedance path to ground for the 25-cycle current. This method is not readily adaptable to synchronous visual type of supervisory control equipment because of the inter-relation of the line circuits. Fig. 5 gives an idea of the connections of the line wires.

The normal condition of the circuits is for *C* wire to be connected between coils *D Q* and *S Q* across the dispatcher's office battery. Thus wires *C* and *C M* carry direct current continuously under one condition. When the set is put in operation *C* wire is dead and wires *D* and *C M* carry current first in one direction and then in the other alternately energizing *D P*-1 and *S P*-1 coils and then *D P*-2 and *S P*-2. This gives the effect of an alternating current of about 6 cycles frequency in wires *D* and *C M*. Later other relays (not shown) set up a similar circuit between *C* and *C M* wires. During the *pulsing* on *D* and *C M* wires, wire *S* may be energized so that current flows in either direction. This is shown in the following table:

Circuit condition	Wire *C M*	Wire *D*	Wire *C*	Wire *S*
1. At rest..................	Energized continuously.......		Energized continuously.......	
2. Stepping or selection......	Pulsating d-c. reversing direction	Pulsating d-c. reversing direction		Pulsating d-c. may or may not reverse
3. Operation...............	Pulsating d-c. reversing direction		Pulsating d-c. reversing direction	

A consideration of these circuit conditions shows that a balance coil system could not be worked out with the synchronous visual supervisory system.

In general, it may be said that any satisfactory drainage system for a four-wire supervisory circuit, where induced 25-cycle currents above one ampere must be removed, will be expensive to build, bulky and cumbersome to install, and will require considerable mounting space.

Previous to this time, the Westinghouse company had completed its experimental work on a new type of supervisory control known as the visicode. The fundamental difference is that this system uses only two line wires and operates by means of d-c. unidirectional impulses. This circuit is so ideally suited for eliminating the effects of low frequency, high-voltage and high-current induction that it was decided to rebuild the West Chester equipment. The circuit which was used is shown in Fig. 6.

The reactor shown in each end of the line wires is the key to the successful application of this circuit. The alternating current flows in both line wires in the same direction at the same time. The windings are so connected that the reactance is practically zero, and only about 25 ohms resistance in the reactor and 50 ohms external resistance limit the current to ground. Thus a large induced current can flow continuously in the two supervisory line wires without flashing the protector tubes or interfering with operation. During tests, the equipment functioned without failure even when short circuits were applied to the contact line circuit while the relay counting chains were operating. This was accomplished with counting relays which were sensitive to less than 0.05 ampere direct current.

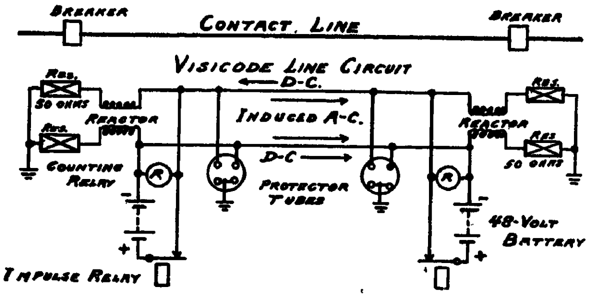

FIG. 6—SCHEMATIC LINE CIRCUITS FOR SYNCHRONOUS VISUAL TYPE SUPERVISORY CONTROL

Since the d-c. impulses flow in opposite directions in the reactor winding, a maximum of reactance exists. The impulses were timed for approximately eight per second, and the reactor was designed to give an effective resistance of more than 500 ohms at this frequency. This circuit permits paralleling a number of stations on the same pair of wires.

The changes were completed on the four stations on the West Chester Division about September 1, 1930. Since that time the same high quality of operation has been obtained as with supervisory equipment of standard design. The synchronous visual set which operates between the dispatcher's office and D-1 substation has a rather short line circuit and is not so closely located to contact line circuits. For this reason this set was not rebuilt. The original supervisory equipment on this branch continues to give good operation.

The supervisory cable along the West Chester branch has an induced sheath potential of considerable magnitude, due to the cable being carried adjacent to the track at approximately the same elevation as the catenary construction. This particularly applies at times of trolley short circuits, or when the trolley circuits are fed stub end over a relatively long distance. The lead sheath of the cable carrying the Wawa supervisory conductors has been grounded through resistances such as to limit the current flow to the values allowed by the cable manufacturer. This grounding decreases the induction on the wires inside the cable because the effect of the sheath current opposes the induction from the contact line. The ground connections are applied at the proper intervals so that the potential to ground cannot exceed a reasonable voltage. This prevents any hazard to a lineman if in contact with the sheath when a short circuit occurs on the trolley line.

The control cable for the West Philadelphia D-1 system is approximately one mile in length. The cable installed was of such size as to permit duplication of control conductors in a manner similar to that on the West Chester branch. It had this marked difference in that the control cable was not installed on poles, but in an underground duct system. As a matter of fact, approximately half of this cable is placed in temporary wooden trunking adjacent to the tracks, as the duct system was not available when the cable was installed. It developed that the lead sheath carried rail return current which under conditions of short circuit on the 11,000-volt trolleys, would reach a value sufficient to melt the lead. This difficulty was overcome by segregating the cable from the rail return circuits with a low value of insulation. This trouble was not serious and was readily overcome.

When this type of supervisory control equipment has been properly adjusted it operates with very little maintenance. However, it is essential that the maintainer be familiar with the circuits and have the skill required for adjusting telephone-type relays. A man who lacks this ability may do more harm than good. The relay cases should be sealed so that only authorized persons can get at the relays. It is quite common for this type of supervisory control equipment, after its proper adjustment has been proved by service, to go for many months without removing the relay covers for inspection or maintenance.

Inspection periods, where equipment is in a clean neighborhood and is operating satisfactorily, can be extended to as long as four months. Companies having large installations usually develop a program suited to their own conditions as determined by their experience. More frequent inspections are desirable where the atmosphere is dirty and also while the equipment is new. Frequent operation of the equipment is desirable. It keeps contacts clean and all moving parts operating freely. All supervisory apparatus should be operated at least once a day, and the power apparatus should be operated if conditions permit. While unnecessary experimenting cannot be allowed, it should be remembered that the authorized maintenance men must have frequent enough contact with the apparatus to keep familiar with it. Otherwise, the quality of their work and speed in restoring faulty equipment to service are greatly impaired. The continued success of a supervisory installation depends on proper maintenance and the importance of this cannot be over-emphasized.

The energy for operating the supervisory equipment is supplied from storage batteries. Twenty-four cell groups, nominally 48 volts, are used at each substation and at the dispatcher's office. The batteries are charged by either rectigon or tungar chargers. The substation and supervisory batteries are entirely separate from each other so that the supervisory system will not be affected by grounds on the power control circuits.

The charging rate is adjusted so as to supply the continuously connected load and maintain a terminal voltage between 50.4 and 52.8 volts (2.1 to 2.2 volts per cell). This provides the proper trickle charge for the batteries and keeps them fully charged at all times. Unusual demands on the battery require raising the charging rate for short periods but this is seldom necessary. The condition of the batteries and chargers is checked regularly. This is essential as the whole supervisory system would be out of service if the dispatcher's battery should become discharged.

In conclusion, it may be stated that the two installations of supervisory control in use for a-c. substations operating on the Pennsylvania Railroad on its Philadelphia suburban electrification are in very satisfactory operation. The two major difficulties originally encountered, inductive interference and the training of a properly qualified inspection and maintenance organization, have been overcome. The effects of induction from adjacent conductors which were found to be serious under heavy short-circuit or long stub-end conditions have been taken care of by changing the original synchronous visual type to the visicode type having reactors at each end of the line. The proper maintenance and inspection was accomplished by a careful selection of men for this work and intensively training them.

The results obtained have shown that when the substations are located at points where no control operations are available, or where such points are so distant that the installation of direct control cables is uneconomical, control can be adequately obtained by the use of proper supervisory equipment.

It permits of centralizing the control of a number of stations at one point, allows greater freedom in the selection of substation sites, eliminates the necessity of special operators when a properly manned adjacent control point is not available.

By centralizing the control of a number of stations at one point, it decreases the delay and possibilities of misunderstandings or mistakes which may occur in the transmission of messages or orders by phone or other methods.

It may be safely stated that supervisory control is destined to play an increasingly important part in future railroad electrifications.

Discussion

For discussion of this paper see page 1374.

Operating Experience With Automatic Stations

Part I—Columbia Engineering and Management Corporation

BY GARLAND STAMPER[1]

Associate, A. I. E. E.

Synopsis.—The only proper way to test automatic and supervisory control equipment is to submit it to actual service conditions over a period of time. Since no one operating company can possibly serve as a proving ground for all types of automatic and supervisory equipment under all service conditions, the alternative is the interchange of operating experiences and ideas between the several companies using this equipment.

The Columbia Gas and Electric Corporation has had automatic and semi-automatic stations of various types in operation during the last ten years. It is found that the class of service secured from any type of automatic station is directly dependent upon the excellence of inspection and maintenance. The chief items of trouble experienced in these automatic stations listed in the order of frequency of their occurrence are: graphic meter pens and clocks, circuit breaker auxiliary switches and closing mechanisms, grounds on control circuits, and relays due to obsolescence and loss of adjustment.

The Toronto Hydro-Electric System has long realized the advantages and economies of automatic and supervisory control. As a result, all new stations built since 1920 have been designed for either automatic or supervisory control. The present policy is to design the railway converter stations for automatic control and the distribution stations for supervisory control. The automatic controls have given fairly satisfactory results and the supervisory controls have given excellent results, especially the cable type supervisory. The chief source of trouble experienced with all this equipment has been relay failures. This would be expected naturally since practically all functions are performed by relays of various kinds. However, it is concluded from the results of these experiences that the automatic and supervisory controlled stations when operated properly are equal to and in some respects superior in reliability and flexibility to attended stations.

* * * * *

THE progress in the development and application of the automatic idea in regard to substations is doubtless familiar to all. The automatic principle was first applied to small transformer stations located at a distance from the main source of power and designed to feed suburbs, villages, and adjacent rural districts. These stations generally consist of a step-down transformer bank and one or two outgoing low-voltage feeders equipped with automatic reclosing oil circuit breakers and possibly induction voltage regulators. Since the load on this type of station is comparatively small, the expense of an operating force and the necessary housing for such operators can not be justified. However, the resultant good will and increase in revenue due to decrease in outage time will justify in a short while the small additional expense necessary to install automatic equipment.

As the success of these installations was proved, the application was extended to include larger distribution stations and converter stations for direct current supply to both the Edison and railway systems. As new control schemes and new devices were developed and their reliability improved, the automatic idea has been applied further until at the present time practically all types of stations are being designed for automatic control, either completely or in part. The chief reasons for this wide spread popularity are; first cost is but little more than that of a comparable attended station; reliability and flexibility are as good if not better; operating costs are materially less.

On the Columbia Gas and Electric Corporation System there is installed one or more stations of the several different classes. There are several 1,000- to 3,000-kva. step-down stations for distribution at 4 and 13.2 or 12 kv., with one and two outgoing feeders equipped with automatic reclosing oil circuit breakers and some with automatic induction voltage regulators. There are also several distribution stations having capacities from 3,000 to 8,000 kva. and a maximum of six outgoing automatic feeders. These feeders are all equipped with reclosing oil circuit breakers designed for single pole operation and the transformer bank controls include load response equipment where two banks are installed. Some of these stations have been operating for six years and longer with entirely satisfactory performance. On the supply to the street railway system serving the Northern Kentucky towns, there are completely automatic converter stations equipped with machines having 500 and 1,000 kw. capacity. The control scheme of these machines is designed to function on voltage variation and load demand and includes many other features incorporated in the latest design for this class of equipment. The breakers on the d-c. feeders are designed to open on rate of rise of current and to reclose when the circuit is cleared.

Due to the rapid growth of the d-c. Edison system before the advent of the automatic a-c. network, it was found to be advisable and economical to supplement the larger converter stations with smaller machines located near the centers of concentrated load areas. The control schemes on these machines include automatic starting at predetermined times and automatic stopping determined by the conditions of load and voltage on the system. At the same time in order to increase the

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[1] Design Engineer, Columbia Engg., & Management Corp., Cincinnati, Ohio.

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flexibility and reliability of the entire Edison system supply, the control on all existing conversion equipment was changed to semi-automatic. This scheme included complete starting operation when initiated by the operator, voltage regulation, load limiting devices, and other improved protective functions.

Around the city of Dayton there is installed a double circuit 33-kv. loop having two sectionalizing stations with step down transformer banks for local distribution at 4 and 12 kv. One of these stations is designed for remote control by means of synchronous selector supervisory equipment from the dispatcher's office over two pairs of telephone wires four miles long. The other station is completely automatic and the control scheme is designed to reclose the 33-kv. oil circuit breakers upon restoration of potential on the lines. The distribution voltage at this station is 4 kv. and the feeders are equipped with regulators and single-pole automatic reclosing circuit breakers. The reclosing cycle consists of three reclosures at intervals of 15, 30, and 75 seconds. If at the end of this cycle the fault still persists, all three phases of the breakers are opened and locked out until the feeder has been cleared of faults. At those stations in which street lighting equipment is installed, the circuits are cut in and out of service by means of time switches equipped with astronomical dials. The operation of any of the automatic equipment transmits a signal over a pair of wires to the dispatcher's office and this signal persists as long as the circuit is deenergized. This pair of wires is leased from the local telephone company and is used also for communication between the station and the dispatcher's office.

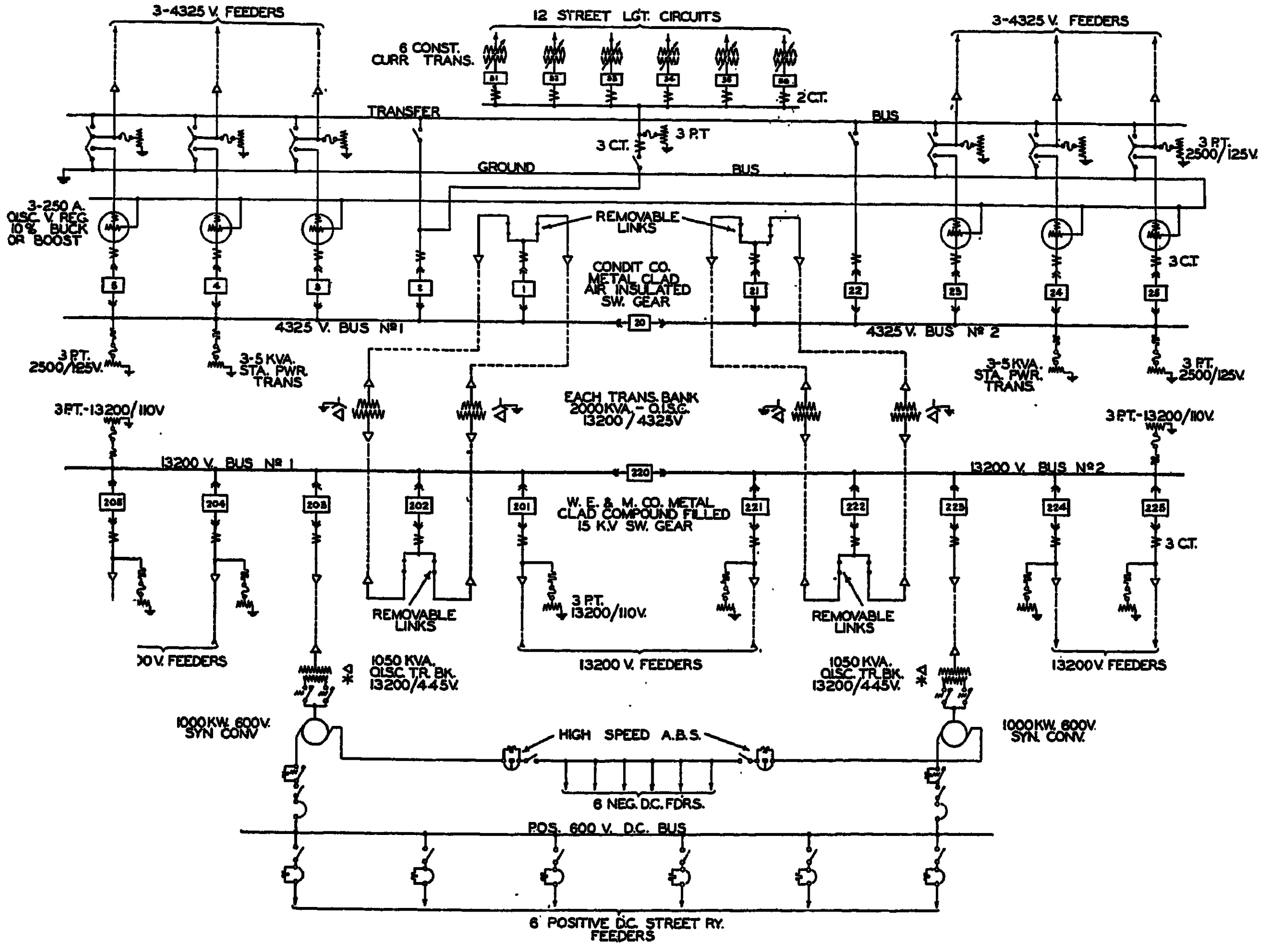

Fig. 1—Single-Line Diagram of Madison Substation Showing the Standard Scheme of Connections

The design and construction of these stations have passed through the cycle of improvement and development of apparatus and devices to increase appearance, safety, and reliability of the entire installation. In the earlier types of station the high-voltage bus structure was built up of concrete cells; the low-voltage bus structure was built of pipe or angle iron; the transformers were equipped with bushings and required a bus structure to make connections; and the regulators were installed in concrete cells with little or no protection. The latest design includes high- and low-voltage metal-clad switchgear, pothead type transformers located outside the substation building, and regulators, when located inside, enclosed in individual concrete cells equipped with oil drains and fire extinguishing apparatus.

The type of service secured from an automatic station depends to a great extent on the degree of excellence of operation and maintenance. In the Cincinnati district there are five automatic station operators whose duties are to inspect, test, maintain, and keep clean all equipment in the automatic stations. There are fourteen automatic stations in this district consisting of; four outlying step down stations having two regulated distribution feeders; five metropolitan step down stations having from two to four regulated distribution feeders; three combination step down and street railway stations having from two to six regulated distribution feeders and one synchronous converter; and two Edison system conversion stations having one 1,875-kw. motor-generator set each. In addition to the care of the above stations, it is the duties of these same operators to inspect, test, and maintain the semi-automatic equipment on the following apparatus: Two 5,000-kva. synchronous condensers, one 1,000-kw. and two 1,500-kw. Edison system motor-generator sets, and seven 3,500-kw. Edison system synchronous converters. This equipment is distributed among six different stations.

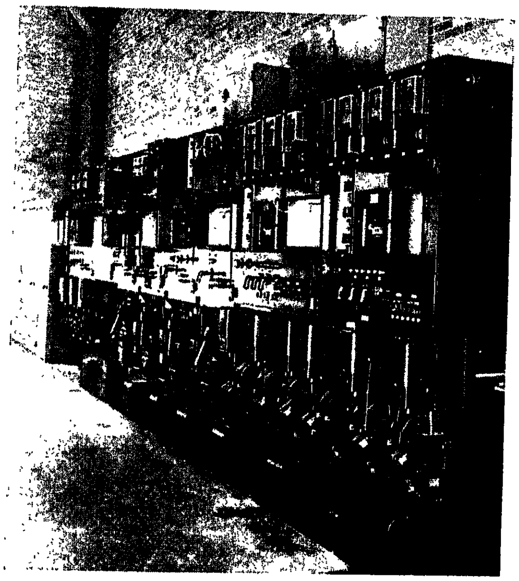

Fig. 2—4,325-Volt Metal-Clad Switchgear Showing Mounting of Relay and Control Equipment

The automatic operators are selected as a rule from the operating personnel of the manually controlled stations. They are men who have had some technical training and have shown some special aptitude for the class of work required of such an operator. They are given a special course of training which consists of serving as a helper for a regular operator and other instructions necessary for a complete understanding of all the various types of automatic installations. At the end of the training period they are required to pass an examination in order to become a regular operator.

There is one operator on duty on each of the three shifts in the day and he is given a regular schedule of work for each day in the week. An effort is made to have the operators visit the more important stations at least once in a day and the smaller stations two to three times a week for a regular inspection. This inspection consists of making the necessary meter and operation counter readings, adjusting graphic meters and changing charts, adjusting battery charging equipment, checking temperatures and general operating conditions of all apparatus, checking indicating lamps, fuses, and grounds on control circuits, and in case of rotating equipment, observing the starting and stopping operations. Once each week the rotating apparatus and all its control equipment is cleaned and necessary repairs made, and a complete check is made of the starting and stopping sequence and the proper functioning of all devices. Once every two weeks the equipment on each reclosing feeder is given the same general overhauling. Once each week all the control batteries are given a slight charge and a complete check of their condition is made. Finally, twice a year all the apparatus in the station is given a complete overhauling by the regular maintenance crew under the supervision of the automatic men.

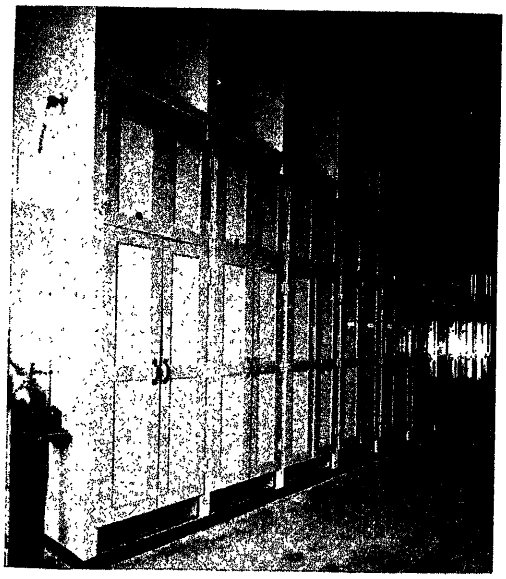

Fig. 3—Typical Regulator Structure Showing Installation of Lux Fire Extinguisher

It is noted in this connection that the operators are not furnished with any standard form for reporting and recording trouble. Neither are they furnished with any chart or standard method for making inspections. The attitude is taken that any kind of form or chart which tends to make an inspection a routine duty will tend to destroy the initiative of the operators and to focus their attention on the completion of the form rather than on the inspection of the equipment. It is fully realized, however, that with this system it is necessary to secure operators of a high degree of excellence and efficiency. In order to keep some check on the proper performance of their duties by the operators they are required to turn in to the chief operator at the end of each day a log sheet showing the stations which they visited during the day, what they did outside the usual inspection, and to note any item requiring attention which they could not remedy. It is unfortunate that this condition exists because many items of interest doubtless are never reported. An effort is now being made to keep a more complete record of operating experiences with these stations.

A few of the most common sources of trouble in automatic equipment are poor clocks and poor pen construction on graphic meters, auxiliary switches on circuit breakers, grounds on control circuits, and the master relay, No. 1, losing its calibration. During the past seven years of automatic station operation in the Cincinnati district there has not been an outage of any consequence due to lack of vigilance and maintenance. This is believed to be a good record and a fine testimonial to the efficiency of these five men. It is estimated that they can properly care for a greater number of stations by relieving them of other extraneous duties which they are called upon to perform.

Upon looking back over the operating records of the distribution stations, it is noted that at least 90 per cent of the faults on a circuit are temporary in nature and that the breakers remain closed after the first or second operation. These circuits having automatic reclosing circuit breakers are equipped with instantaneous overcurrent relays set to operate at a predetermined value of current which is slightly below the safe rupturing capacity of the circuit breaker or the thermal capacity of the regulators. The operation of these relays prevents the reclosure of the circuit breaker until the fault has been cleared and the relays reset. To date there has been only one operation of these relays which was caused by a cable failure near the station. By the use of these relays it is considered safe to install equipment having lower capacity or to make the time between circuit breaker reclosures less than advisable otherwise.

The reclosing cycle for manual stations is 20, 45, and 90 seconds, providing the operator is free at the time of fault to perform these functions. Since the operation of the automatic stations is free of the human element, it is found that these functions are performed faster and more accurately than any operator could perform them. Whenever trouble develops in an automatic station, the operator on duty at the time is immediately dispatched to that station to clear up the trouble and to restore the equipment to its normal operating condition. With only one operator on duty and with more than one station in trouble, the outages are sometimes prolonged undesirably. However, during storm periods when trouble is most likely to occur, another operator is pressed into duty for emergency calls and it has not been found necessary to increase the number of regular operators. The application of semi-automatic control to the Edison system conversion equipment has materially increased its reliability and flexibility and decreased the outage time. It is interesting to note that under conditions of severe system disturbances, the automatic stations have performed the necessary functions faster and more accurately than could be expected of any operator. Since the load dispatcher has sufficient confidence to trust them to perform correctly, he can devote his attention to other pressing concerns.

On the system of the Dayton Power and Light Co. there have been for a number of years several automatic distribution stations in operation. These stations are of the outdoor type having reclosing circuit breakers in individual sheet metal houses. The breakers are equipped with a-c. motor-operated closing mechanisms and 24-volt d-c. trip coils. So much trouble has been experienced with this type of control that no similar equipment is being considered for future installations except in special cases. The auxiliary switches are a perpetual source of annoyance and the centrifugal closing mechanism has a tendency to lose its adjustment and cause the breaker to "pump" or else fail to close altogether. It has been decided that the future installations of this nature shall include solenoid-operated breakers with a control battery or some similar source of supply. Since the cost of the solenoid mechanism is less than the motor mechanism, this compensates to some extent for the additional cost of the control battery.

One of these stations was supplied through a tap connection on the double circuit 33,000-volt loop around the city. Approximately two years ago this station was rehabilitated and 33,000-volt sectionalizing equipment was installed. At this time the control scheme was changed from automatic to supervisory which is operated from the dispatcher's office approximately four miles distant from the station. The only source of trouble experienced on the installation to date has been due to interference by the telephone company from which the interconnecting wires are leased. Another point of some interest in this station as well as in automatic stations in general is the use of diverter pole type motor-generator sets for control battery charging. In case of complete outage on the station it was found that this set could be automatically started and reconnected to the battery without any supervision. It is the practise to float the motor-generator set across the battery at all times.

In addition to the above stations this company has been operating four automatic street railway converter substations for approximately ten years. A great deal of trouble was experienced with these installations as originally designed which was due principally to the types of relays installed. The old plunger and bellows types of relays were not as accurate or reliable as the present induction types and motor-operated timers. Practically all the original relays have been replaced by relays of later design and very little trouble from this source is anticipated in the future. In one station in which two converters were installed for parallel operation considerable difficulty was experienced in securing the proper operation and division of loads. This is an example which shows the necessity for careful and exact specifications and design to secure similar characteristics in machines for this class of service.

It is believed that the automatic station has proved itself thoroughly and that it has a definite application in the distribution of electrical energy on practically all systems. It is to the advantage of all to recognize the economies to be obtained by the application of automatic stations, and there has been enough experience obtained to fully establish their reliability and flexibility. There are a few items which should interest the manufacturers and direct their attentions towards improvement, such as, graphic meters, breaker-operating mechanisms, and some types of relays.

It has been shown conclusively that the key to success in the operation of automatic stations is correct inspection and maintenance of the equipment Recently a proof of this statement was brought very forcibly to the attention of the writer. On the distribution system of one of the subsidiaries of the company there were several small automatic stations which were not giving the type of service expected of them. All manner of trouble was being experienced with this equipment and the frequency and length of outages were becoming a source of great annoyance to all concerned. Upon an investigation of the situation it was found that there were no operators expecially trained to inspect and maintain these stations and that an inspection was made by any employee at whatever time he happened to be near the station. As a result of the long existence of this condition the automatic station was being blamed for the entire situation and was falling into much disfavor. Inspection can be overdone as well as underdone and it is only by experience that the happy and sufficient medium can be attained. Maintenance and inspection result in a saving by minimizing the number of outages and damage due to incorrect operations and failure of equipment. The savings effected by inspection and maintenance beyond a certain point are often overbalanced by the increased operating cost. Finally, since continuity is the keynote of public utility's service to its customers, the automatic station is recommended as a means of securing improved service continuity with a decrease in operating expense.

Part II—Toronto Hydro-Electric System

By F. F. Ambuhl[2]
Member, A. I. E. E.

The rapid growth and expansion of the Toronto Hydro-Electric System from its inception in 1910 resulted in numerous changes and extensions to the stations and distribution system to meet the constantly increasing demand for electric power. Some of the first stations were too small and more or less temporary, making it necessary to rehabilitate these at a comparatively early date.

In 1920, considerable thought was given to automatic control for railway substations and supervisory control for transformer and switching stations. During the years 1921 and 1922, two automatic railway substations and two supervisory control substations were installed on the Toronto system.

The first automatic installation gave a certain amount of trouble when first installed, in that some of the equipment required a considerable amount of attention and necessitated slight changes being made to certain parts of the equipment. After these weak spots had been eliminated, however, the equipment gave satisfactory results.

The first installation of supervisory control, unlike the automatic control, gave satisfactory results from the beginning, there being very little maintenance required on this equipment, which was undoubtedly due to the simplicity of the scheme used.

After the first eighteen months all automatic and supervisory equipments were giving satisfactory operation and these results, together with information on more recent developments in this class of equipment, led the Toronto Hydro-Electric System finally to adopt the policy of locating moderate sized stations near the economical load centers and equipping them for automatic or supervisory control. From this time forward all new substations were equipped for automatic or supervisory control.

All supervisory stations are operated from the nearest manual station, the operators of which are under the jurisdiction of the system load dispatcher.

At present there are installed on the Toronto system, five automatic and nine supervisory equipments, with three more supervisory equipments going in this year. All of the automatic stations were new installations, whereas two of the nine supervisory equipments were installed in old stations rehabilitated and equipped for supervisory control.

Four different types of automatic and four types of supervisory control have been used by the Toronto system.

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[2] Asst. to Chief Engr., Toronto Hydro-Electric System, Toronto, Ont., Canada.

Automatic Equipment.

- Westinghouse Automatic Railway Equipment.
- General Electric Co. Automatic Railway Equipment.
- Brown Boveri Automatic Mercury Arc Rectifier Equipment.
- Automatic Synchronous Condenser Equipment developed by the T. H. E. S.

Supervisory Equipment.

- Westinghouse Synchronous Visual Supervisory Control.
- General Electric Distributor Type Supervisory Control.
- General Electric Synchronous Selector Type Supervisory Control.
- Toronto Hydro-Electric System, Monowire Cable Type Supervisory Control.

In addition to the above automatic and supervisory equipment, there is a Gamewell signaling system which is used for giving signals to the load dispatchers when switches automatically open in small unattended transformer stations where supervisory control has not been provided.

SOURCE OF ENERGY FOR SUPERVISORY AND CONTROL EQUIPMENT

Item 1—In general storage batteries and motor-generator sets are installed as the control energy source and floating battery operation has been adopted as standard. In some cases, the motor-generator set is supervised, in others it is not.

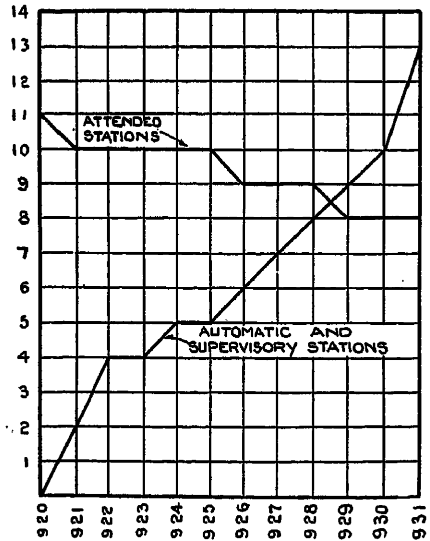

FIG. 4—CURVES SHOW NUMBER OF SUPERVISORY AND AUTOMATIC STATIONS AS COMPARED TO ATTENDED STATIONS SINCE 1920

Item 2—*Supervisory and Control Circuits*—The cable used for supervisory control is lead-covered paper-insulated, impregnated and insulated for 1,500 volts. Each conductor is 16 gage and the cable is laid up in twisted pairs. All cable is underground and is privately owned; also it is used for a number of services such as supervisory control, telephones, telautograph services, remote and totalizing metering.

The installation of supervisory equipment has increased constantly on the Toronto Hydro-Electric System as will be seen by referring to curves of Fig. 4, showing the total installations by years and taking into account the three stations which are now under construction.

OPERATION

The benefits derived from automatic and supervisory control have in general been quite satisfactory and are accepted today as efficient and economical features of power distribution. This method of controlling stations has, however, changed the whole aspect of the operating problem and is of such importance that both operating and manufacturing engineers are giving careful attention to the results obtained, with a view to making further improvements in the methods of control, and particularly the apparatus used in connection with such schemes.

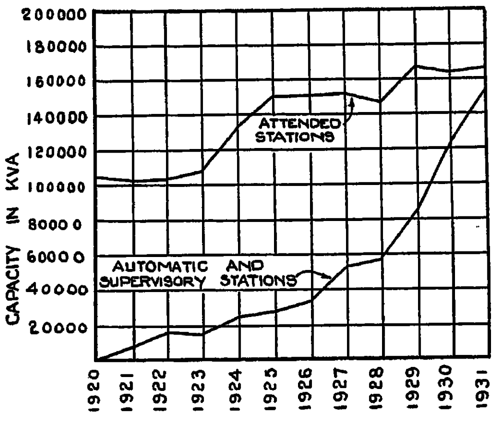

FIG. 5—CURVES SHOWING THE INCREASE OF INSTALLED CAPACITY OF SUPERVISORY AND AUTOMATIC STATIONS AS COMPARED TO ATTENDED STATIONS BY YEARS.

A great deal has been done during the last ten years in developing equipment of the desired characteristics to be coordinated into various schemes of operation as required by the apparatus controlled and which may be depended upon to give reliable operation.

The rapid strides that have been made in this class of equipment have not, however, enabled the manufacturer to give all of his equipment a thorough test, particularly where time and certain operating conditions enter into the problem, and it, therefore, devolves upon the operating companies to make these tests over a period of time under the operating conditions for which the apparatus was intended.

The best method of determining the reliability and efficiency of automatic and supervisory equipment is to try it out for a period of time under service conditions.

While there is a number of properly coordinated, well designed systems of automatic and supervisory control in use, experience has shown that even though great care may have been taken in the manufacture of the equipment, certain weaknesses develop in service which have to be overcome. These are usually minor troubles which very often develop shortly after the equipment goes into service and can generally be rectified without any alteration to the equipment. It is important that proper maintenance be provided as the number of faulty operations may be reduced materially if the maintenance men, looking after the equipment, are thoroughly familiar with the equipment from the beginning and are able to locate and correct the trouble immediately when it occurs.

In order to give some idea as to how this equipment has operated, it is proposed to give a brief description of the various schemes of control used by the Toronto Hydro-Electric System and the performance of each over a period of years.

AUTOMATIC SYNCHRONOUS CONVERTER STATIONS

Two schemes of automatic control for synchronous converter stations have been used by the Toronto system, the General Electric scheme in which a drum controller initiates the various operations in proper sequence, and the Westinghouse company's scheme, in which these steps take place through the guidance and control of various relays and interlocks which function according to a predetermined plan in a step-by-step fashion. The ultimate results being the same in both cases, namely, that of starting up and shutting down the station as required. In both of these schemes, it is the practise to arrange for starting up on load demand which is determined by a suitable contact making voltmeter, and shutting down when the load is reduced to an uneconomical point. In other words, when the trolley voltage is reduced to a minimum amount by the increased load, a contact making voltmeter energizes a relay which starts the sequence of operations for starting up the station. These will be referred to as Scheme A and Scheme B in the paper.

Scheme A. In Scheme A, a motor-operated drum controller is started through the action of a low-voltage relay as mentioned above. This causes the high-tension breaker to be closed, energizing the transformers and is followed by the closing of the a-c. starting switch, impressing sufficient starting voltage across the rings to bring the machine up to synchronism. When full speed is reached, the converter fields are excited from a small direct current generator, which is driven by the motor on the drum controller. This gives a positive method of obtaining correct polarity. The converter is then connected for self-excitation and the running switch closed, impressing full voltage on the machine and giving normal field excitation. As soon as the machine reaches normal voltage, the d-c. line switches are closed, connecting the machine to the line through the current-limiting resistors in the machine circuit and if the current taken by the machine is not excessive, the current-limiting resistors are immediately cut out. The controller then remains at rest and the converter operates normally on load until the current supplied by the station falls below some predetermined value, when a low-current relay operates, starting the controller toward the off position, thus shutting down the station.

Operating Results of Scheme A. Scheme A was first installed in the North Toronto station in 1922. This station was primarily used to boost the voltage on the north Yonge St. line and supply power to the car barns across the street from the station. A 1,000-kw. converter was installed at first and a second machine was added later. These machines supplied power to the railway over six feeders, protected by automatic carbon-break circuit breakers.

In addition to the current-limiting resistors which are automatically cut in or out as the load demands, these converters are also protected by a type JR high-speed circuit breaker connected in the negative lead to the machine. The equipment in this station has given very satisfactory results for over nine years though a few troubles have been experienced, some of which are enumerated below:

1. When first installed, Nos. 2 and 3 timing relays gave trouble and were replaced by the manufacturer.
2. The No. 30 field relay did not function properly and the coil on this relay was changed, after which no further trouble was experienced.
3. Some trouble has been experienced with the break-bands on the brush lifting mechanism breaking, making it necessary to replace these.
4. An open circuit in the exciter generator, used for correcting polarity, caused considerable operating trouble before it was known that this was the cause. This was an intermittent trouble which was not apparent at all times. This was repaired, after which no further trouble was experienced.
5. In addition to the above, various relays have required adjusting and light repairs, though it cannot be said to be excessive.

The use of a drum controller, through which the various relays are energized in their proper sequence, has probably helped to reduce relay contact trouble, as such a device is very sturdy and the contacts of which are very reliable. The drum controller has also been found very useful in checking trouble as the whole operating sequence can be gone through and inspected in steps by operating the drum controller by hand and in this way each relay circuit can be checked separately. In general this equipment has given very satisfactory operation though no doubt improvements have been made on some of the devices which will still further reduce the troubles which are now being experienced.

Scheme B. In Scheme B the rotary transformers are energized through the operation of a low-voltage relay and subsequent relays, similarly to the other scheme, after which, the starting contactors are closed and the machine then builds up in speed in the usual manner. During the time interval of starting, the polarity is checked and if found incorrect, is reversed automatically by slipping a pole. This is accomplished by means of a polarized motor relay, driven by a d-c. motor having a permanent magnet field and with the armature connected across the converter commutator. While the converter is accelerating, the voltage across the commutator is alternating and the relay motor armature merely tends to oscillate. As synchronism is approached, the voltage merges into a direct current potential. The relay armature then revolves in one direction or another, dependent upon the polarity of the machine and turns a drum contactor. If correct polarity is obtained, by the order in which the contacts are closed, the starting contactor drops out, the running contactor is closed and the brushes are lowered. If, on the contrary, the converter builds up with incorrect polarity, the relay again operates in such a way as to repeat this operation.

When correct polarity has been obtained, the starting contactor is opened, the running contactor is closed, the brushes are lowered, and the d-c. switches are closed. This connects the machine to the load, through the current-limiting resistors which are then shunted out in steps by contactors which close through the functioning of accelerating relays. The machine remains in operation until cut out of service by light load conditions similarly to that of the previously described scheme.

Operating Results of Scheme B. Scheme B was installed in the first automatic railway station in Toronto, the station being used for boosting the voltage on a long cross town line in the north part of the city. This equipment, to a large extent, consists of standard relays, together with a number of specially designed devices coordinated to give the proper sequence of operation.

This station has been operating satisfactorily now for nearly ten years though numerous troubles were experienced when it was first installed, requiring considerable attention and modification of some of the devices before satisfactory operation was obtained. Some of the principal troubles which occurred when this equipment was first installed are given below:

1. Mica insulation broke down on grid resistors.
2. Trouble was experienced with the latching relay on the *E* switch which was modified to eliminate further trouble.
3. Trouble was experienced with the contacts of pallet switches controlling the main contactors, making it necessary to modify these devices, after which no further trouble was experienced.
4. The contactor coils burnt out repeatedly and were finally rewound with a larger number of turns to avoid over heating.
5. Converter bearing thermostats became inoperative, due to warping of the fiber plunger rods.
6. Brush lifting motor burnt out, also the brush lifting mechanism gave considerable trouble. This mechanism was modified and the original motor replaced with a larger motor, after which no further trouble was experienced.
7. Considerable trouble was experienced with the contacts arcing over on the No. 7 polarized motor relay, which was also modified and the trouble eliminated.
8. There was also a number of other minor troubles, the nature of which is not on record.

Most of the above troubles occurred during the first year, though after they had been eliminated, the equipment gave very satisfactory operation.

BROWN BOVERI AUTOMATIC MERCURY ARC RECTIFIER STATION

In 1929 the Ossington Station was increased from 1,000 kw. to 2,200 kw. by installing two mercury arc rectifiers in the station building and placing the transformers and switches outside. In this way, the station could be more than doubled in capacity without increasing the size of the building, and as the rectifiers did not require any special foundation, it became only necessary to move the rotary converter with its automatic equipment into one of the larger stations where more railway machine capacity was required and set the two 1,100-kw. mercury arc rectifiers on the floor of the Ossington Station.

The completed station is a full automatic rectifier plant consisting of two 1,100-kw. nominally rated rectifier units. Energy is taken from a 13,200-volt, three-phase 25-cycle source and converted to 600 volts for traction service. Each rectifier and its transformer is capable of carrying the following load, based on the nominal rating of 1,100 kw. at 600 volts:

Per cent load	Amperes	Duration
100	1,833	Continuously
150	2,750	2 hours
200	3,666	1 minute

Automatic Features. The automatic features can be roughly divided into four groups: Plant control, a-c. closing and reclosing, vacuum pump control, and the protective group.

Plant Control. The rectifier plant is arranged to start and stop according to the demand. Either unit may be made the leading unit, the other one being switched in or out according to the demand on the first. The first feature is known as low-voltage low-current control, the second is the overload control.

Another important automatic feature of the plant control is the lockout control. Should the leading unit be in serious difficulty it will be locked out and automatically transmit all signals received to the lagging unit which then becomes the leading unit.

It is also possible to start and stop the station or any of its units manually, while retaining all other automatic features.

A-C. Closing and Reclosing. The rectifier is controlled through the oil circuit breaker which connects the unit to the a-c. supply. The circuit breaker is closed according to signals received by the a-c. closing and reclosing controls, all conditions being correct. Should the breaker fail to close, the reclosing control will attempt to close it two more times at definite time intervals. If it does not close the last time, the rectifier will be locked out and the spare unit switched in if desired.

The d-c. breaker is controlled by the oil circuit breaker through electrical interlocks.

Vacuum Pump Control. The vacuum pump is automatically controlled according to signals received from a contact making vacuum meter.

Either or both the a-c. and the vacuum pump controls can be entirely cut out and replaced by purely manual control.

Protective Features. The rectifier is protected against sudden and continuous overloads, high-voltage surges, high temperature, water failure and operation with poor vacuum. The d-c. breaker opens on reverse current.

Operating Results. This rectifier equipment has given very satisfactory operation though some operating trouble was experienced when the apparatus was first installed. These are enumerated as follows:

1. Insulator on excitation anode was found cracked, due to incorrect size and improper packing.
2. Ignition coils burnt out several times, due to relay sticking. This was overcome by modifying the relay.
3. Poor contact on control relay prevented the rectifier from being cut in.
4. Trouble on overload relay contacts prevented the second unit from coming in.

The above defects have all been remedied and no trouble whatever has been experienced with this equipment during the last ten months. It might be mentioned that this equipment has carried loads considerably in excess of 150 per cent load several times, without showing any signs of trouble.

WESTINGHOUSE HIGH-SPEED VISUAL SUPERVISORY CONTROL SYSTEM

The Westinghouse high-speed visual supervisory control system is an all relay system embodying the principal of step-by-step synchronous selection. Apart from the control board, the equipment is mounted in two steel cabinets, one of which is located in the dispatcher's office and the other at the outlying station. At the outlying station there is also a number of interposing relays which serve to relay the signals from the relay cabinets to the units controlled. Four wires are used between the dispatcher's office and the distant station. By means of two of these wires and a synchronous control circuit, selecting relays are kept in step and moved from point to point in a definite sequence, that is, corresponding relays are operated simultaneously at the dispatcher's office and outlying station. The remaining two wires of the trunk line are switched by the operation of these relays from one apparatus control unit to another. The apparatus units at the substation are connected to a set of selecting relays and the dispatcher's control keys and supervisory signaling lamps are connected to a similar set. The selecting relays must operate in synchronism at every step or not at all.

Proper lamp signals notify the dispatcher should the system cease to function. All apparatus is normally at rest. The cycle of synchronous selecting operations takes place when the dispatcher initiates an action or when an apparatus unit changes position at the outlying station.

Operating Results. The synchronous visual supervisory control described above has been installed in four stations of the Toronto Hydro-Electric System, the first being installed six years ago; the second four years ago and the other two, three years ago. This equipment has given satisfactory operation on the Toronto system, though it cannot be said to be entirely free from trouble. The troubles experienced in almost every instance are however of a minor nature and are usually found to be relays requiring slight adjustment, or contact trouble.

Control-key contacts, battery equipment and fuse troubles also contribute to the cause of faulty operations. There are some instances where certain relays cause more trouble than others.

In the case of the Danforth station, as will be seen from the performance chart in Table I, forty-five cases of relay troubles were reported in five years, of which fourteen were due to latching relays sticking. Operating records of the other stations using the same kind of equipment, though more recent, do not show the latching relays to have given any more trouble than the other relays.

There has been a number of faulty operations for which no cause was found, also a number of faulty operations has occurred which was found to be due to main apparatus trouble.

G. E. DISTRIBUTOR TYPE SUPERVISORY CONTROL

The distributor type supervisory control was installed in the Parkdale station in 1928. This was one of the early developments of supervisory control and uses a modification of the printing telegraph distributor and polarized relays. The purpose of this distributor is to minimize the number of connecting line wires between stations and at the same time allow the transmission of control and indicating impulses in a predetermined sequence, thereby taking the place of two connecting line wires between stations for each switch or unit to be controlled and indicated.

Considerable trouble was experienced with this type of equipment due almost entirely to the distributor mechanism.

TABLE I—PERFORMANCE CHART

Station	Type	Control positions	Months in service	Supervisory relay trouble	Control key trouble	Battery equipment trouble	Fuse Trouble	Human factor	Line troubles	Outages due to supervisory trouble	No. of operations per year
Market	T.H.E.S.	30	114	4	4	2	5	1	None	1	W 100
Keele St	T.H.E.S.	17	102	3	2	2	1		1	1	175
Carlaw	T.H.E.S.	18	11	5	2	2	2		None	0	400
Danforth	W.E.& M. Co	50	60	45	2	5	2	3	None	8	3,000
Parkdale A.	G.E.Co.	46	21	7*							
				98†	4	1		3	None	11	300
Parkdale B.	G.E.Co.	46	8	2	0	1		2	None	2	325
Defoe	W.E.& M. Co	30	53	9	1	2	1	2	None	8	175
John St	T.H.E.S.	30	18	2	1		1	3	1	1	100
Wiltshire A.	W.E.M.Co.	40	47	10	3		3	0	None	8	2,000
Wiltshire B.	W.E.M.Co.	40	47	10	4	4	2	0	None	4	200
Stirling Rd.	W.E.&M.	30	1931								
Glengrove	G.E.Co.	30	1931	Last three not yet in operation							
Duke & Geo.			1931								

*Relays †Distributor

The motor-driven distributors, one being installed at each end of the control system, are operated continuously and must be kept in synchronism if proper operation of the control system is to be obtained. Numerous faulty operations were experienced as a result of this part of the equipment getting out of order, and the matter of keeping this equipment working properly became so difficult that it was finally decided to have the manufacturer change this system to the more recent development known as the synchronous selector type of supervisory control. This change was made during the spring of 1930.

G. E. SYNCHRONOUS SELECTOR SUPERVISORY

This new system which replaced the distributor type supervisory control in the Parkdale station is essentially a direct system of control and indication, using the familiar type of rotary selector, such as used for automatic telephones, which step in synchronism to transfer the control and indication line wires from one circuit to another as selected by the dispatcher.

The relays, selectors, control keys and indicating lamps are more or less standard devices so coordinated as to insure a proper sending of control impulses and indicating the positions of the various units controlled.

The synchronous selector system is divided essentially into three independent circuits designated as control, indication, and synchronizing. All three use a common return. The equipment at the dispatcher's office is connected to the equipment at the substation by four line wires, all of which must be free from grounds. The dispatcher controls the supervised unit in the substation over the control circuit, and the indications from the supervised units are returned to the dispatcher over the indication circuit. The selector equipment at the outlying station is made to operate in synchronism with the selector equipment in the dispatcher's office by means of current impulses sent over the synchronizing circuit. The principle of this scheme is very similar to that of the distributor type in that all control operations are performed over four wires and distributed by means of synchronized switching devices at the sending and receiving ends.

Results of Operation. This equipment has been in operation since April 1930 and has given very satisfactory operation. By referring to the performance chart, Table I, it will be seen that for the first eight months, only two troubles have been experienced with the relays—both of which were minor troubles, and one with the battery equipment, which was due to the brushes of the motor-generator set sticking in their holders.

T. H. E. S. MONOWIRE SUPERVISORY CONTROL

Four stations of the Toronto system use a cable system of supervisory control which was developed by the Toronto system and is called the "monowire supervisory," since only one wire or channel is used for each unit controlled and two wires or channels being common to all controlled units. The monowire system differs from other cable systems used at present in that only one wire is used instead of two, for each unit controlled and indicated.

Description. The principle of this scheme and mode of operation, will be best understood from the drawings, in which Fig. 6 is an elementary diagram showing the fundamental circuit. Fig. 7 is the circuit of Fig. 6 with indicating features added. Fig. 8 is one form of a complete commercial circuit, with additional alarm and safety devices added.

All of the figures show control for one unit only. It is obvious that one or a plurality of similar controls may be used as required.

In Fig. 6 two common buses, positive and negative (1 and 2) are energized from some source of voltage; a battery 3, is shown. These buses are continuous from controlling station to distant station and serve to energize all units which may be connected to them. Considering the monowire unit as we may term it, a single-pole double-throw switch with terminals 4 and 5 serves to connect the monowire M to either of the two buses as desired, thus in turn energizing either of the coils T and C, depending on which polarity is closed across the switch. Thus if the two coils T and C are actuating coils controlling a circuit breaker it can be opened or closed depending on the position of the switch 4-5. In practise the coils T and C are usually not continuously energized, and for this reason, and to eliminate a series connection between the coils T and C and the two buses, we insert in the circuits of the coils pallet switches 12 and 13 for opening and closing in accordance with the operation of the breaker being controlled. Switch 12 is closed when the breaker is closed; switch 13 is closed when the breaker is open.

The circuit of Fig. 6 suffices for the mere operation of a circuit breaker, two operations being performed over the monowire M. Indication as to switch position is obtained by the arrangement of Fig. 7 in which like letters and numerals of designation refer to corresponding parts. While the coils T and C of Fig. 7 may control a circuit breaker directly they are here shown as relays which by means of contacts and standard control circuits, not shown, initiate the tripping and closing of a circuit breaker when energized. This arrangement has a number of practical advantages and enables one to adjust the electrical values of the coils T and C to the most favorable point for satisfactory operation, as dealt with below.

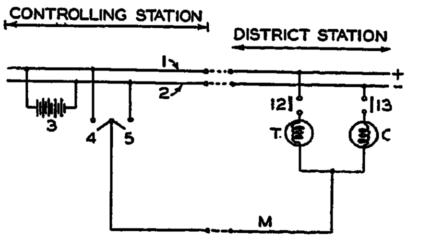

Fig. 6

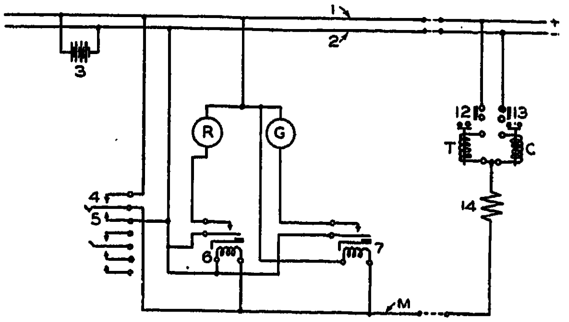

Fig. 7

Further, the control key 4-5 is shown as being of the telephone type.

Relays 6 and 7 and indicating lamps R and G which may be colored red and green respectively are shown in Fig. 7. The manner of their operation is as follows:

Assume that the control key 4-5 has been closed in the 4 position thus energizing the closing relay C and closing in the circuit breaker. On closure, switch 13 opens and 12 closes, thus completing a circuit from positive bus 1 through 12-C and 14 to contact 5 of control key, now open, and preparing the way for the opening of the circuit breaker. A circuit also exists, when the circuit breaker is closed, from positive bus 1 through 12, T, 14 and relay coil 6 back to negative. Relay coil 6 is thus energized and closing its contacts completes a circuit through the red lamp, thus giving an indication that the breaker is closed. While current for the energizing of 6 thus flows through coil T, it is not sufficient in amount to operate the relay T. In other words relay coils 6 and T are chosen of such differing values of resistance that 6 will operate and T will not when placed across the bus potential. This is an essential feature of this control scheme.

Exactly the same sequence is gone through when the breaker is opened or opens by itself, the green light lights through relay 7, operating relay 7 being energized by a circuit from negative through 13, C, 14, and 7 to positive. A resistance 14 can be inserted in the monowire lead if desired so as to adjust line resistance to the proper value for correct relay operation and so enabling the use of standard relays over varying distances. The line resistance obviously varies with the distance between stations.

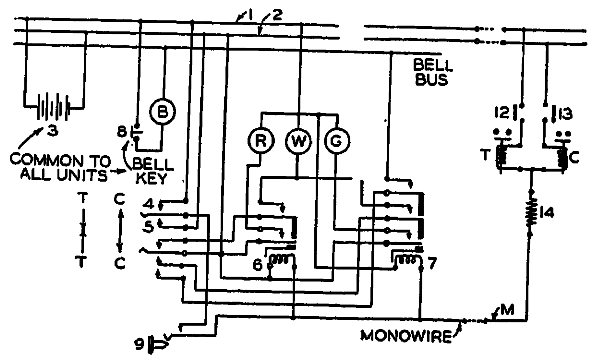

Fig. 8

While operation and indication of position is achieved by the arrangement shown in Fig. 7 it is also desirable to provide for the giving of an audible or visible alarm should the circuit breaker or other equipment controlled, change position independently of the monowire control through protective relay action, etc. This is achieved in the arrangement shown in Fig. 8 where an additional indicating lamp W (white) together with additional contacts on the relays 6 and 7 are shown. A bell B and bell key 8 are also shown. The bottom contacts on the control key 4-5 have also been connected up. In this arrangement the control key is of the locking type.

The sequence of this additional alarm circuit is as follows: assuming that the operator desires to close the circuit breaker, he operates the control key 4-5 to place it in the closed position. When this is done the bottom contacts on the key are also closed making two circuits from negative, through relay contacts on 7 to white lamp and to bell bus respectively. Since at the instant of operation of key 4-5, the circuit breaker being open, relay 7 is still energized together with the bell circuit, showing that key and breaker positions do not agree. The operator may if he so desires, eliminate the ringing of the alarm bell by depressing the bell key 8.

The master key 9 has been added to eliminate malicious or accidental operations through inadvertence and the operator according to the scheme of Fig. 8, is required to operate the master key 9 to complete the operation desired and to send closing energy over the monowire *M*. Master key 9 also clears direct positive or negative potential from the monowire and so permits of the correct functioning of lamp relays 6 and 7.

On the closure of the circuit breaker, relay 7 is deenergized through the pallet switch 13 opening, and the green light is open-circuited together with the alarm light *W* and the bell circuit, the red light circuit also being energized through the operation of its relay 6, this latter being energized through the pallet switch 12.

Should the circuit breaker now open through overload relay action or some other cause, relay 6 becomes deenergized and relay 7 energized, thus causing the red light to go out and the green one to light up as in Fig. 7, now, also the white one lights up and alarm bell rings. This gives the operator an audible warning of trouble and a glance at his key-board shows him that one particular circuit breaker is concerned through the signal given by its white light. He can then eliminate the ringing of the bell and put out the white light by moving the key 4-5 to the trip position so as to agree with breaker position.

The bottom arm of key 4-5 has an upper contact the circuit of which is made through relay 6 to the white lamp, so that when the key is turned to the open position from the closed, with the circuit breaker closed, the white lamp gives an indication that the key in this position also does not agree with the breaker position.

Thus, superimposed on the ordinary green and red light indication we are enabled over the one monowire circuit to provide an additional supervisory indication which shows when the control key does not agree in position with the controlled equipment at the distant substation and which also gives an audible indication of the independent operation of the controlled equipment.

Operating Results. This system of control has given very satisfactory operation during the past ten years. There has been very little trouble with the switch operations though a certain amount of trouble has been experienced with the signal devices. The reason for this is that there are no relays in the control circuit at the dispatcher's office and only one relay, or perhaps two, at the outlying station; also there are only two contacts to be made at the dispatcher's office and one, or in some cases two, at the outlying station for each operation.

The relays used in this system are standard relays which have been tested under severe operating conditions and while they have not been free from trouble they have given very satisfactory operation. The operating results of the cable supervisory installations will be seen from the performance chart, Table I. The very satisfactory operation of this scheme has resulted in its being used where the distance between stations was short and the total cost of installation, including the cost of supervisory cables, was less than other schemes using synchronized switches at the sending and receiving ends for reducing the number of wires.

It might be mentioned that at the Market station, 1¼ miles from the control station where a twenty-five unit equipment was installed, the total cost of the installation, including supervisory cables, was paid for by the elimination of operator's salaries in three years.

This scheme has also been used for internal station switch control where a considerable saving in the cost of control cable and conduits was effected.

General Remarks. By referring to the performance chart, Table I, showing the various kinds and number of faulty operations, of the supervisory equipment it will be seen that most of the trouble was due to faulty relay operation, a condition which one would naturally expect since the apparatus consists mostly of relays. The relay troubles are due to a number of causes such as residual adjustments, contact trouble, loose nuts and screws, dirt, etc., all of which are usually found to be minor troubles and are experienced more in some types of equipment than others.

Trouble has also been experienced with control and contacts, battery equipment, poorly soldered joints, loose fuses, fuses blowing, etc., though troubles from these sources have been very few. It has been the experience of the Toronto system that these troubles are usually not general but are due to certain weak spots in each type of equipment, which, after they have been rectified, give much more satisfactory operation. Experience has also shown that the more recent equipment has given less trouble than earlier equipment, which would indicate that the manufacturers have, to a considerable extent, overcome the troubles experienced with the earlier equipment.

Discussion

SUPERVISORY CONTROL FOR A-C. ELECTRIFIED RAILROADS

(West and Griffith)

OPERATING EXPERIENCE WITH AUTOMATIC STATIONS

(Stamper and Ambuhl)

E. J. Rutan: From these papers one gets a contrast between the opinion of a manufacturer in regard to the maintenance required on this type of apparatus, and the more definite statements of the user. There is no doubt but that a definite program of adequate, possibly frequent maintenance is required in order to have apparatus of the type covered in these papers function satisfactorily day in and day out. The method of developing the program and the costs are of interest.

The cost limits have not been brought out by the authors, but these in general, must not exceed the cost of operating a station with attendants. It would be of advantage if the authors gave some idea of the amount that can be economically expended for maintenance when consideration has been given to the additional capital investment involved in the supervisory and automatic equipment. A partial answer has been given by Mr. Ambuhl through his curve in Fig. 4, which shows that since 1920 there has been a marked increase in automatic and supervisory stations, with a decrease in attended stations. From this it may be concluded that they must have found it economically feasible or such a continuous growth would not have occurred. Specific details in regard to comparative costs, however, would be welcome.

The major difficulties which Mr. Stamper reports as representing the chief troubles in the automatic stations are with graphic meters and circuit breaker, auxiliary switches, and mechanisms. These, I feel, should not be listed as difficulties chargeable to automatic stations, in view of the fact that such equipment has been in service on practically all systems many years; long before automatic stations were attempted. If difficulty is experienced with equipment of this sort, either the available engineering knowledge has not been used in specifying the equipment originally, or the maintenance experience has not been utilized to keep such apparatus in proper condition. It is known that some types of graphic instruments are not as reliable as others, but there are instruments available which will give good performance from the time a new chart is placed in the instrument until it is necessary for the inspector to return to renew the chart. As far as auxiliary switches and circuit breaker mechanisms are concerned, it is felt that the experience in the industry is such that these devices, if of a properly specified design and good manufacture, can be maintained with long intervals between inspections and still be free from troubles so that they should not appear as troubles for automatic stations. The other difficulties which are listed are in line with those to be expected in connection with the operation of supervisory and automatic stations.

In developing a definite maintenance program, the following suggestions are given:

In connection with the installation of the equipment, the men who are to be responsible for maintenance should work along with the installation crew, and be responsible for the checking of the apparatus for proper functioning before initial operation. This insures that the men will have gained experience and knowledge of the equipment while testing for faults before operation is attempted. The maintenance schedule then can be set up on a rather frequent basis, perhaps weekly or bi-weekly. These men should be carefully supervised and should report in detail their findings on each type of relay and equipment. After a few months, a study of their data will show that certain of the devices can have the maintenance period extended to a month or three months. Following the same procedure on the new basis, it is possible to arrive at a program in which only a few of the units may receive attention once a month, other units on a three months' basis and some units may go for six months or longer. While this program is in operation, it would be desirable to have several men working in the crew so that by the time the final program is set up there would be available on the system a number of employees capable of handling the maintenance work and emergency calls when they may arise.

In connection with maintenance programs, I would like to urge on the technical committee a more definite effort to collect the operating experience of the various companies who may have supervisory control systems or automatic stations so that it may be made available more readily to all those in the Institute interested in such problems. Those who have had experience with such equipment know that a period of six months or a year, is required in order to know the weaknesses as well as the advantages of a system. It is then found that when a complaint is made to the manufacturer about the weaknesses, he has developed a new system which he would advance as the answer to the troubles. It is necessary, however, to continue the maintenance of the system already installed. Conditions have been such in recent years that advancement has been so rapid that the maintenance experience which the operating men are obtaining on the various systems is not being made available quickly enough, and in a collective way, so as better to judge the engineering qualities of the newer developments which the manufacturers advise us represent the last word, at least for that current year.

As a definite program, I would urge the Automatic Stations Committee to consider collecting maintenance data and making a report similar to the manner in which information on the operation and performance of protective relays was collected by the Protective Devices Committee some years ago. I think such a program adopted by this committee would be very helpful to users and prospective users of supervisory control systems and automatic substations.

C. E. Stewart: The use of lead-sheathed cable in underground ducts as applied by the Toronto Hydro Electric engineers makes an ideal arrangement for the functioning of any type of supervisory equipment. The line wire troubles as listed by Mr. F. F. Ambuhl in the performance chart attest to this fact. Maximum freedom from interference caused by mechanical, human, or electrical factors is obtained by this arrangement.

In connection with this performance chart on four-wire systems, it would be interesting to know if the relay troubles listed were in the common group of relays or associated with the individual circuit group. Also, were the outages listed as due to supervisory trouble actual outages on individual power circuits or does this represent the time the supervisory equipment was inoperative?

The use of the monowire or direct wire system for short distances over privately owned wires is undoubtedly the most economical for first cost. Whether the sacrifice in flexibility to meet future rearrangement of the supervisory equipment due to changed operating conditions, future growth, etc., offsets this advantage is questionable and must be determined by local conditions.

Usually a reduction in line wires in supervisory systems is accompanied by a sacrifice in operating facilities in one form or another. This, I believe, is true of the monowire system described, in that no indication is given to the operator when a breaker trips instantly on overload, after being closed. Under such conditions an operator would not know, if the supervisory equipment failed to function or if the breaker actually closed and opened.

A sincere attempt has been made in our commercial systems to incorporate this feature for the operator's information. Information relative to line wire and battery voltage conditions is given to the operator in our selective systems. An expression of opinion from operating companies as to the actual value of these points should be interesting and valuable.

The program of maintenance on automatic stations outlined by Mr. Stamper is without doubt one of the major reasons why this type of equipment is making such a fine record for itself. Recognition of the necessity and the acceptance of responsibility for periodic inspection has been followed by a practical and sane program. To keep pace with the march of modern progress, practises in regard to maintenance have changed materially. In many industries there was a time when maintenance consisted chiefly of repair and replacement activities. Today more time is spent on *preventative* maintenance. A point of perfection will never be reached where it can be disregarded on automatic switching equipments. Since the inception of these equipments, however, we have invested heavily in means to reduce this item of expense. Much progress has been and is being made in simplification of design and improved types of devices. Design progress has necessarily been slow. For economic reasons devices and equipment designed for manual operation were first utilized in this new art. These have been modified and replaced as the principles of automatic switching of power apparatus have been learned. There is much yet to be done. By no means has the automatic station reached its highest point of perfection or its widest application.

In reference to the difficulties on graphic meters, would it not be advisable to place these in the dispatcher's office by utilizing the present developed types of telemetering equipment? It would seem that they would be more useful to the power dispatcher in such a location. They would then receive the attention which the present designs are accustomed to receive in manually-operated stations.

Much progress has been made within the past two years on interlock design and motor-operated breaker mechanisms, so that highly satisfactory devices are now available.

In Fig. 2 a view of metal clad equipment is shown with associated relay and control equipment. Has this arrangement of mounting worked out satisfactorily?

M. E. Reagan: Mr. Stamper has advanced the argument that maintenance charts are, in general, not good for getting a complete accurate record of operation. This may largely depend on the type of form used. Some operators have found this to be the one method of obtaining good maintenance records. It would be interesting to get a résumé of experience on different classes of automatic equipments.

Messrs. Stamper and Ambuhl give interesting data on operation. The outstanding fact that equipment gives more trouble when first installed is not entirely explained by making replacements with better equipment. It is true that each year sees an advance in the reliability of automatic equipment. More money is spent on factory test before shipment and the various sources of trouble are "weeded out" as experience is gained. The operating personnel maintaining the equipment is responsible for a large share of credit in getting better equipment performance after becoming familiar with it.

Garland Stamper: It is suggested by Mr. Rutan that the value of this paper would have been enhanced if a cost comparison between automatic and manual stations were included. This question was considered and it was decided that such a comparison was entirely beyond the scope of this paper. However, a recommendation has been made to the chairman of the Committee on Automatic Stations that additional information be accumulated on this subject during the coming year. Such a study is of necessity so complex and involved with a study of the entire distribution system that it merits a separate consideration.

Mr. Rutan objects, also, to the inclusion of graphic meter and circuit breaker mechanism troubles in the list of automatic station troubles. It is true that these problems were present before the advent of the automatic station and they are still present to occupy the time and attention of the operators. Since the trend of present day practise in maintenance is towards prevention rather than repair and replacement, it is felt that all those items which do cause trouble should be included in this list. It is true, however, that the design of this equipment has been improved to such an extent that this trouble is materially less than formerly.

Mr. Stewart suggested that the graphic meters be replaced by telemetering equipment with the receivers in the dispatcher's office. In the majority of cases this scheme is not feasible due to the cost of installing or renting the necessary interconnecting wires.

Mr. Stewart questioned, also, the desirability of mounting relays and control equipment on hinged panels attached to the front of metal clad switching units. This arrangement saves space and is somewhat cheaper in first cost than a separate switchboard, due to the saving in control conduit and cable. The chief objections to this type of construction are:

(1) Crowding of instruments due to the limited space.

(2) Inconvenient mounting height on the larger units.

(3) Danger incurred by the maintenance men, due to the proximity of high-voltage circuit breakers which may fail on the occurrence of a feeder fault.

F. F. Ambuhl: Mr. E. J. Rutan mentioned the necessity of adequate inspection and maintenance on automatic and supervisory control.

On the Toronto System, we have found it essential to have specially trained men to do this work. One man is required to look after inspection of the automatic equipment and any work to be done, is done by maintenance men who are familiar with the automatic equipment. Two men are required for inspection and maintenance of the supervisory equipment. These men are specially trained for inspection and maintenance and also work along with the construction men on all new installations of supervisory control.

As regards the economy effected by using supervisory control, it has been the experience of the Toronto System that after taking into account annual fixed charges on the investment, including the cost of cable between stations, also maintenance and repairs, the supervisory equipment will pay for itself in from three to five years, (for stations such as used by the Toronto System) depending on the type and number of positions used; also on the distance between, and location of stations.

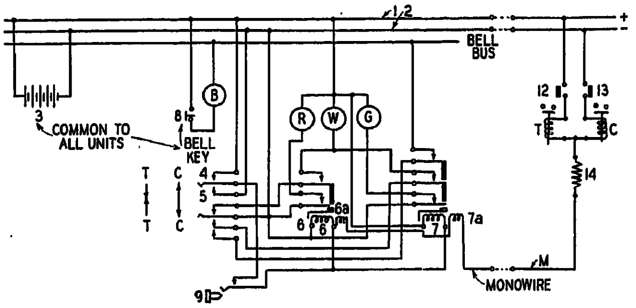

Fig 1

In Toronto, two men are required on each shift, which with a relief operator, makes a total of seven men for each manually controlled station. This item alone has justified the installation of supervisory control in Toronto.

Mr. C. E. Stewart has asked if the relay troubles listed were in the common group of relays or associated with the individual group. If I understand Mr. Stewart correctly, no trouble has been experienced with the rotary selectors and some types of relays in the common group of other schemes of supervisory control, though the troubles experienced are not confined to any particular group or circuits but vary in the different schemes used.

On one scheme, the latching relay in the common group has given a great deal of trouble; also trouble has been experienced with residual adjustment and contacts in the individual groups.

The outages, listed on tabulated report as due to supervisory trouble, are assumed as feeders or equipment temporarily out of service due to the inability of the operator to put such equipment in service by supervisory control, and which was found due to defects in the supervisory equipment, thus making it necessary to send a man to the remote station to put the equipment in service manually or by rectifying the trouble. This sometimes happens when feeders or equipment are automatically tripped out and are ready to go back into service.

Mr. Stewart's comments concerning sacrifices in operating facilities are true in so far as the original monowire equipment is concerned. The lamp indication during switching operations agreed only with key position, irrespective of breaker position, since the operation of closing the control key automatically short-circuited one lamp relay and energized the other with full line potential. However, this objectionable feature has been overcome in the latest development, by providing each lamp relay with a second coil, through which the monowire circuit is carried. (Fig. 1.) When the control key contact is made, the ampere turns on the first lamp relay coil due to operating current, balance and oppose those due to the circuit made from bus to relay, to control key, to position key and thence to bus. Consequently no change in position occurs, until the apparatus controlled has changed its position. The other relay of the pair which before was deenergized, is now excited with monowire operating current and so also remains in its original position. The moment the operating current is broken by switch closure or tripping, the auxiliary coils are no longer effective and the lamps change indication, thus giving an indication of the switch position at all times.

Automatic Combustion Control

BY C. H. SANDERSON[1] and E. B. RICKETTS[1]
Fellow, A. I. E. E. Non-member

INTRODUCTION

THE successful application of automatic devices to power plant equipment for control of combustion has been very largely a development of the past ten years. During this period confidence in automatic operation was greatly strengthened by its success in other fields, particularly in that of the electric substations and hydroelectric generating stations. Moreover its development and application has had wholehearted approval and assistance of engineers and operators due to the ever increasing urge for higher efficiencies and lower fuel and labor costs.

Remote control of combustion equipment has become a necessity for the large modern boiler installations for much the same reasons that necessitate its application to the electric equipment. A boiler having a capacity in the order of 1,000,000 pounds of steam per hour may require as many as eight controls; two for induced draft fans, two for secondary fans, one for primary fan, two for excess pressure valves, and one for fuel feeder motors. This equipment is of necessity scattered over so wide an area that direct control would require six or eight men instead of one or two as when all controls are concentrated at one point.

Consider a large modern power plant having a number of boilers, each with centralized hand control, attended by two men; close regulation of combustion will often require their combined effort. It is usually impracticable, because of space requirements and the nature of the control to concentrate it at one point. Therefore, the imagination will be put to little effort in visualizing the release of this small army of men from a tedious and exacting service by an apparently "made to order" application of automatic control. The word "apparently" is used advisedly as there have been and there still exist many problems in the perfecting of the application. A brief review of the historical background, with its changes in apparatus and costs of fuel and labor, which has brought about the extensive modern application of automatic combustion control may be of assistance to a clearer understanding of these problems.

HISTORICAL

The typical large boiler plant of thirty years ago presents to memory a multiplicity of small boilers, rarely exceeding 600 hp. in individual capacity. Because of the small size of the apparatus, most of the auxiliary equipment such as dampers, blowers, water gages, etc. were within reasonable reach or view of the operator.

The firing was largely done by hand, requiring a considerable number of men for a given output. Men were normally stationed where they could easily make the few adjustments that were necessary. The fireman was picked for strength rather than intelligence and his qualifications have been aptly stated as being "a strong back and a weak mind."

The boiler room was usually hot, dirty, and generally uncomfortable; a place where one would stay no longer than necessary. Viewing such a boiler room in the light of present day conditions one would be impressed by the almost entire absence of meters, gages, and other aids to good operation. The reaction would be of wonder that good results were ever obtained under such adverse conditions.

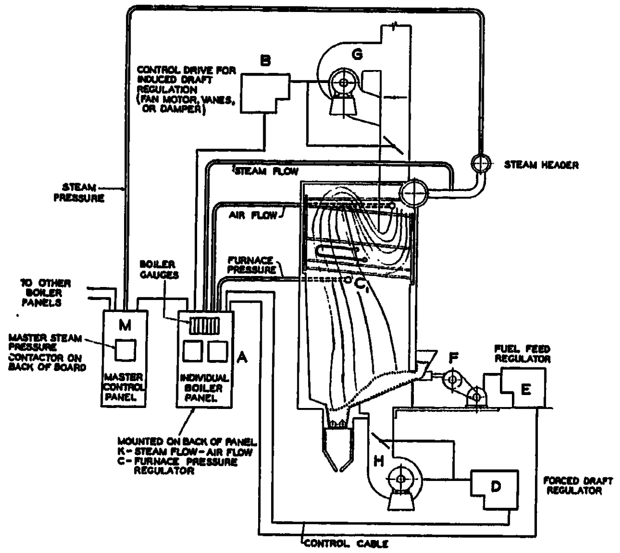

FIG. 1—OUTLINE OF BAILEY SYSTEM

When boiler tests were made, meters, gages, thermometers, and apparatus for gas analysis were temporarily installed and a number of test men continually watched conditions and made adjustments. With those aids, efficiencies were obtained which compare very favorably with those of today. When the tests were completed the instruments and test men were removed and the fireman was literally "left to his own devices" which, as previously mentioned were mainly conspicuous by their absence. He could know but little of what was going on in the boiler and could not devote much time to efficiency studies after shoveling 25 or 30 tons of coal during an eight-hour watch. It is therefore no matter for wonder that daily efficiencies obtained in routine operation failed by 10 per cent or more to equal those obtained under test conditions. In spite of these handicaps, due to the prevailing low cost of fuel and labor, steam could be generated for about half of what it costs today. Therefore the present urge for higher efficiencies and lower labor costs was nonexistent.

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[1] The New York Edison Company.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

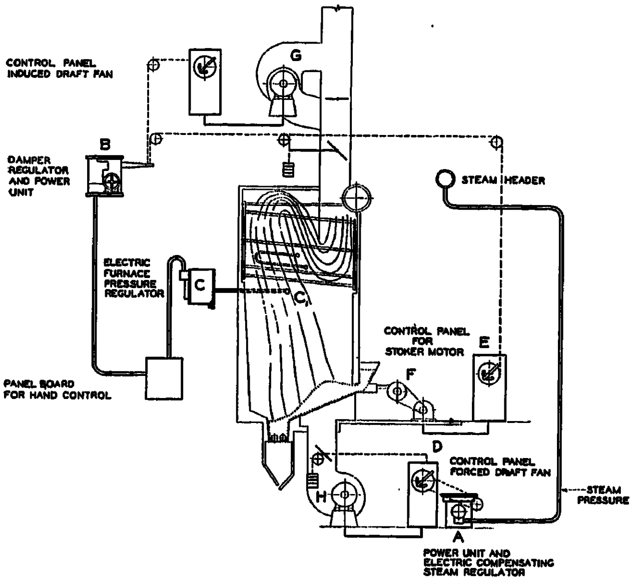
CONTROL PANEL INDUCED DRAFT FAN
G
B
DAMPER REGULATOR AND POWER UNIT
STEAM HEADER
ELECTRIC FURNACE PRESSURE REGULATOR
C
C_1
CONTROL PANEL FOR STOKER MOTOR
E
F
PANEL BOARD FOR HAND CONTROL
D
CONTROL PANEL FORCED DRAFT FAN
H
STEAM PRESSURE
A
POWER UNIT AND ELECTRIC COMPENSATING STEAM REGULATOR

FIG. 2—OUTLINE OF ENGINEER CO. SYSTEM

The earliest attempts at automatic control employed damper regulators actuated by steam pressure. With the development of automatic stokers and forced draft, regulators were applied to blower engines and to the maintenance of balanced or nearly balanced furnace draft. The earlier apparatus was very crude in its mechanical features, and had the bad habit of being either all "on" or all "off," thus producing a steam pressure chart having frequent and wide fluctuations.

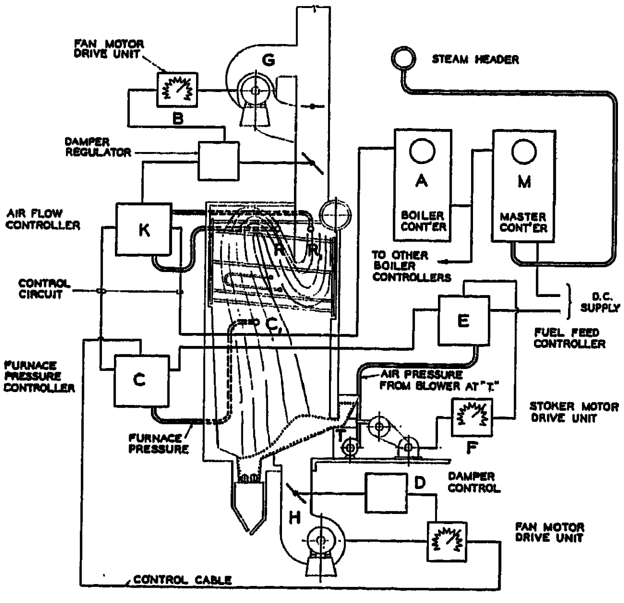

FIG. 3—OUTLINE OF LEEDS AND NORTHRUP SYSTEM

The next step in the development was a departure from these unreliable automatic devices in the application of permanent instruments to indicate draft and rate of coal feed, together with better facilities for hand control. Where hand control of the entire plant was centralized a considerable improvement was realized due to the uniform loading of the various boilers and to the much closer regulation of the steam pressure.

The development of the modern boiler plant necessitates the consideration of large units where in many cases the auxiliary equipment may be located a hundred feet or more from the control point, and the use of large stokers requiring varying air pressure in their different sections, the use of pulverized fuel, gas and oil for which efficient operation requires closely coordinated regulation of fuel and air. The necessary complement of gages and meters for a single boiler has been very greatly increased while of economic necessity the number of men has been reduced. The unit cost of labor and fuel has trebled in the last thirty years and consequently comparatively small savings in these items may justify the expenditure of material sums for new equipment to produce such results.

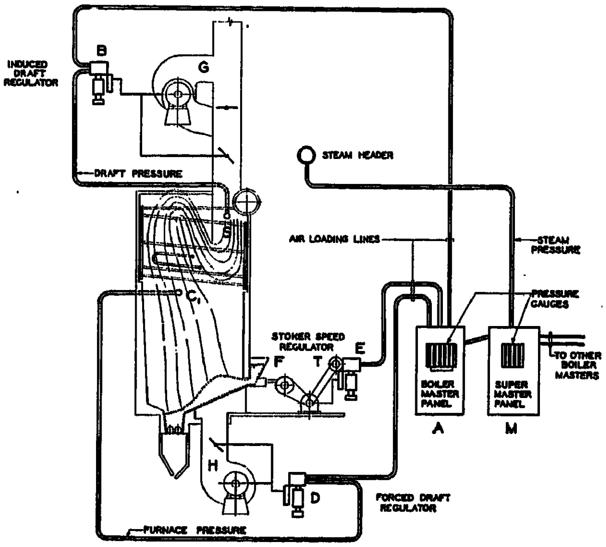

FIG. 4—OUTLINE OF SMOOT SYSTEM

REASONS FOR AUTOMATIC CONTROL

Because of the usually small amount of steam storage, fluctuations in station load are almost immediately reflected in steam demand; and if maximum efficiency is to be consistently maintained these fluctuations in demand must be met by corresponding changes in fuel and air supply. When a multiplicity of boilers supply the same steam system any change in station load should normally be divided evenly between these boilers. If the operating force is sufficient in numbers, highly skilled and supplied with adequate instruments, results can be obtained with a well planned manual control which compare favorably with the best automatic control. However, the automatic control is ever alert to perform its functions and its chief advantage lies in its ability to act simultaneously throughout the plant, thus permitting a reduction in the required number of skilled operators.

Large modern boiler installations are commonly equipped with push-button type of remote control which represents probably the most easily and quickly manipulated type of manually operated equipment. The cost of such a system represents a large portion of the cost of a complete automatic control system as it may be incorporated as a part thereof.

ADAPTING THE CONTROL TO THE INSTALLATION

While control systems can be adapted to most any type of boiler auxiliary equipment, the smoothness of operation is often complicated by the inherent characteristics of the apparatus controlled.

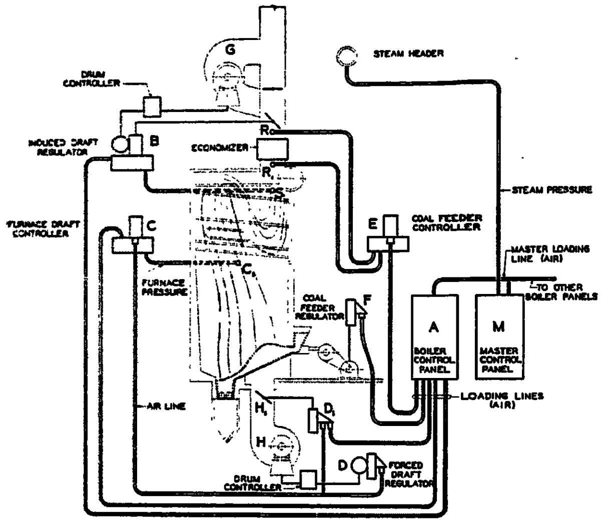

FIG. 5—OUTLINE OF HAGAN SYSTEM

The ideal combination of control and auxiliary equipment is one which gives immediate response to a change in demand by delivering to the furnace a proportionately changed amount of fuel and air. Some types of equipment are inherently capable of approaching this ideal more closely than others and an understanding of these characteristics will be helpful in an understanding of what may be accomplished with automatic control.

Air Supply. Air supply control is usually actuated by draft at the boiler outlet. Some types of draft producing equipment can be controlled for smooth changes in small increments; others operate with large increments.

Among the types of draft equipment producing smooth changes are:

1. Chimney draft—damper control.
2. Steam-driven fans. Driver control.
3. D-c. motor-driven fans. Driver control.
4. Wound-rotor a-c. motor-driven fans. Driver control.
5. Single-speed a-c. motor-driven fans. Damper control.

Among the types of draft equipment producing abrupt changes of relatively large magnitude are:

1. Multispeed induction motor-driven fans. Driver control.
2. Multispeed induction motor-driven fans. Driver and damper control.
3. Multispeed induction motor-driven fans. Driver and vane control.

Large modern boiler installations employing long stokers commonly require a supply of air at several different points at different pressures. This condition makes necessary the provision of several windbox pressure controllers which may be adjusted either for a constant ratio or for varying ratios on the different sections of the stoker as the conditions may demand. Similarly, pulverized fuel installations may require individual regulation of the primary, secondary, and tertiary air pressures.

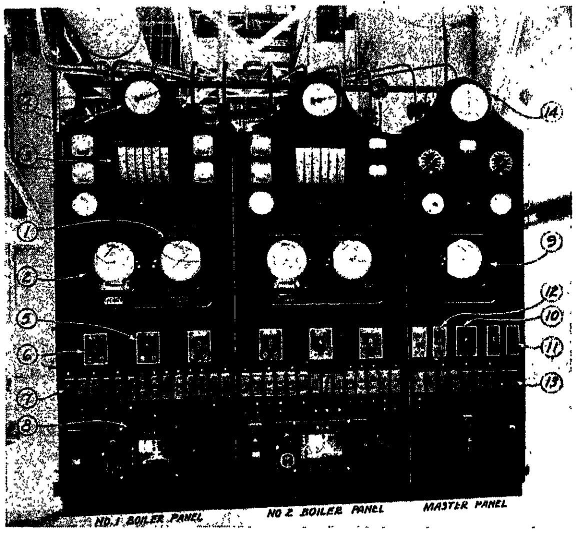

FIG. 6—EXAMPLE OF A BAILEY CONTROL PANEL

1. Boiler meter with steam-flow—air-flow and furnace-draft contactors
2. Feed-water meter
3. Multipointer gage
4. Boiler drum water level indicator
5. Combustion-control selective switch for complete automatic control, partial automatic control, or push-button control of fuel, forced, and induced draft.
6. Reheat-steam temperature-control switch for automatic or push-button control of the high-pressure steam valve to the steam reheater
7. Fan- and feeder-motor switches
8. Automatic control box for power-control safety valves
9. Steam-pressure and feed-water heater pressure recorder with master pressure contactors
10. Master control switch for combustion control system
11. Reheat steam distribution control switch for automatic or push-button control of the reheat steam distribution valves
12. Boiler feed-water-pump control switches for automatic or push-button control of the pump motor drum controllers
13. Feed-water pump-motor switches
14. Steam header pressure gage

In most systems of control involving the supply of air for combustion under pressure it is necessary to provide an auxiliary control to prevent the occurrence of a pressure above atmosphere in the furnace. This control is actuated by furnace draft and usually functions as an emergency or readjustment mechanism on the forced draft fan.

Many different types of automatic control are available for application to the different systems used for producing draft or air supply. For example; in natural draft installations the automatic control is usually applied to the stack damper. For adjustable-speed motors and steam turbines the speed of the driver only is automatically controlled.

In some pulverized fuel systems employing a unit system, it is necessary to introduce a time lag in the air supply equipment to allow for the interval between the increase or decrease in the coal supply to the mill and the time when this change in supply reaches the furnace.

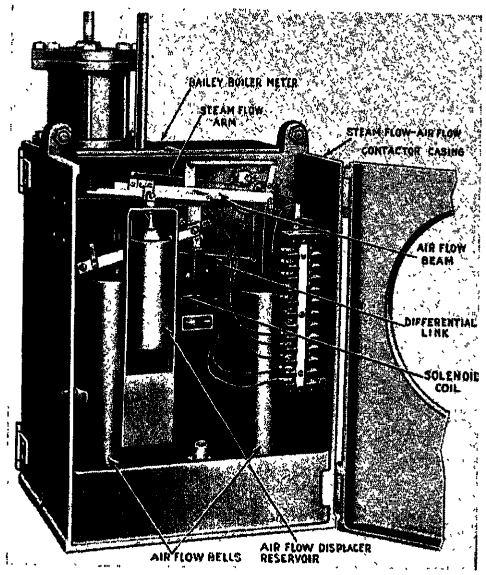

FIG. 7—BAILEY STEAM-FLOW-AIR-FLOW CONTACTOR

Air Measurement. In a few cases it is possible to measure the air supply by means of an orifice or some other metering device installed in the air supply line. However, usually due to the fact that considerable quantities of air enter through openings in the furnace setting, it is necessary to base the air control on the flow of the gases of combustion rather than the air supply. The medium most often used for this control is the pressure drop through a bank of boiler tubes. When the tubes are reasonably clean this method of air control is sufficiently accurate for all practical purposes. When the tube bank becomes partially covered with slag, manual readjustment of the air supply controller is necessary unless an additional control connection is made with some form of CO_2 meter to provide automatic readjustment.

Fuel Supply. Types of fuel supply equipment have a very marked influence on the quickness of response to a change in load and on the effect on combustion conditions of large abrupt changes in draft.

A. The following types of supply equipment afford immediate response:

1. Gas
2. Oil
3. Pulverized coal—bin and feeder system
4. Stokers carrying a heavy fuel bed

B. The following types have a slow response (from one to fifteen minutes):

1. Pulverized coal—unit system
2. Stokers carrying a light fuel bed

C. All types of fuel supply are adversely affected by large abrupt changes in air supply, the disturbance in all cases being more marked with water-cooled furnaces than with refractory furnaces. The effect on some of the more widely used systems is as follows:

Conditions	Effect
1. Stokers with deep fuel bed	Smoke and temporary loss in efficiency
2. Stokers with light fuel bed	Blowing bare spots on grates, loss in efficiency and capacity over a considerable period
3. Pulverized coal Bin and feeder system	Possible loss of ignition
4. Oil and gas	Possible loss of ignition
5. Pulverized coal. Unit system	Probable loss of ignition

Fuel Measurement. Where coal is the fuel the measurement of fuel supply is commonly derived from the revolutions of the fuel feeding mechanism, each revolution of which is assumed to inject a given quantity of combustible material into the furnace. Unfortunately, however, coal is one of those natural products which is prone to wide variation in physical and chemical characteristics which are reflected in the fuel value per revolution of the feeding mechanism. Consequently, correct ratio of fuel and air can only be maintained either by occasional manual readjustment of the coal feeding mechanism or by an automatic air adjustment mechanism actuated by a CO_2 meter or a steam-flow—air-flow meter.

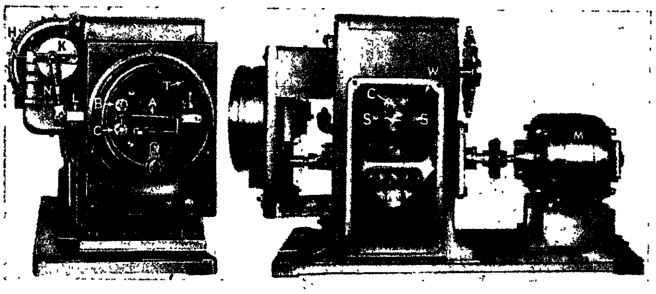

FIG. 8—REGULATOR AND MASTER CONTROLLER—ENGINEER COMPANY

Legend

M	Driving motor	*A*	Contact arm
P	Sprocket wheel	*B* and *C*	Contacts
W	Wheel on ratchet	*H*	Compensating hand screw
C	Center of pawl shaft	*K*	Crank for opening contacts *B* or *C*
S	Solenoids	*N*	Link
T	Bourdon tube	*L*	Lever

Sequence Interlocking of Control. In nearly all large modern boiler installations, it is necessary to provide sequence interlocking between certain of the control points. For example; it is usually necessary to provide that a shut-down of the induced draft fan will simultaneously interrupt the coal feed and air supply and that the coal feeding mechanism will not over travel beyond the ability of the induced draft fan to take away the products of combustion. In many installations employing pulverized fuel firing there is a low limit below which combustion becomes unstable and a further reduction of coal and air feed might cause the fire to blow out.

Wherever automatic combustion control is applied, each boiler unit is provided with a simple and ready means for changing from automatic to hand control as is necessary under emergency conditions such as the interruption or partial interruption of the supply of coal, air or feed water to an individual boiler.

Control-Power Supply. To insure continuity in the operation of the control system, the supply of the medium through which the control impulses are carried to the various regulators must be positively safeguarded by the provision of two or more independent sources of supply and a ready means of changing from one source to another.

Pneumatic and hydraulic systems were originally employed but with the advent of electrically operated remote control, electricity has been adopted by a number of manufacturers as the medium for automatic control.

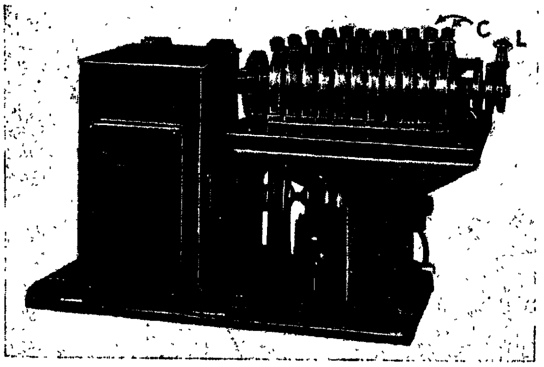

FIG. 9—ELECTRIC SENDING AND RECEIVING UNIT—ENGINEER COMPANY

C Contacts *L* Lever for group adjustment

The electrical control drives are designed to use either alternating or direct current at any voltage from 110 to 250.

SYSTEMS

Probably no two power plants ever built were exactly alike. Comparison of any one with another as regards the detailed requirements of an automatic combustion control system reveals a surprising lack of standardization. Naturally the same is true of the control systems employed and therefore only a generalized performance specification together with brief descriptions of several typical systems will be given.

In all systems a master controller transmits impulses actuated by steam pressure variations simultaneously to the various individual boiler control panels from which radiate the controls of fuel and draft. The control performance is, in general, as follows:

1. An increase in plant load causes an increased demand for steam and therefore a drop in steam pressure.

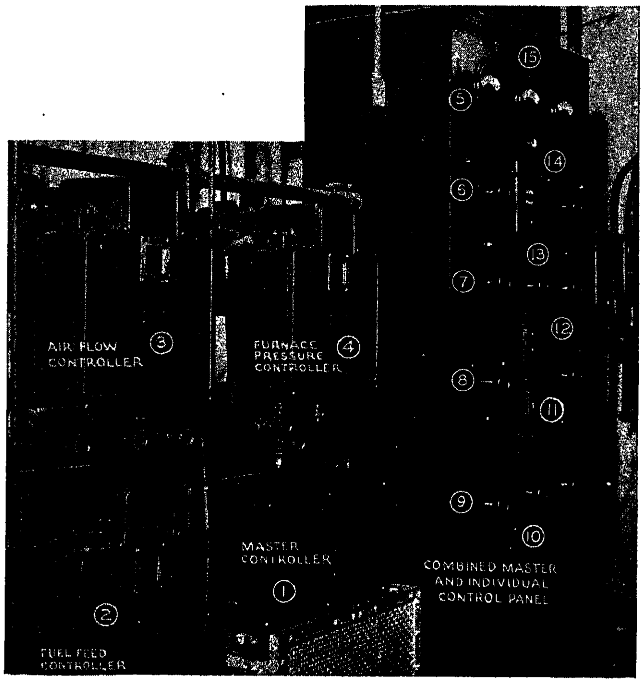

FIG. 10—CONTROL PANELS—LEEDS AND NORTHRUP

1. Master controller
2. Fuel-feed controller
3. Air-flow controller
4. Furnace-pressure controller
5. Combustion-rate indicator
6. Combustion-rate rheostat
7. Selector switches
8. Motor-generator field rheostats
9. Motor-generator starting switches
10. Main control switch
11. Fuel control selector switch
12. Fuel control push-button station
13. Voltmeter transfer switch
14. Annunciator
15. Voltmeter

2. Changes in the steam pressure are converted into forces or impulses which actuate a regulating device controlling the rate of fuel and air supply to the boiler in proportion to the load. Forces or impulses which are not linear are adjusted in the regulator.

3. Since the regulator can only control mechanical forces which under normal conditions will supply the correct amount of fuel and air, variations from the assumed normal conditions must be compensated by changing the relation between these mechanical forces which supply either fuel or air so that the correct amount of each is supplied to the boiler. A furnace pressure regulator and a CO_2 recorder will detect and make adjustments for variations from normal conditions. These variations are caused by slagging or damp coal or an irregular supply of coal.

4. Controls can be set so that certain boilers maintain a constant output while other boilers take the variations, and can be provided with maximum and minimum stops to limit the range of output.

5. Control of any or all functions can be accomplished separately or in groups, either directly or indirectly, as required by individual conditions.

6. Some of the available systems are provided with audible and selective visual signals to indicate equipment failure.

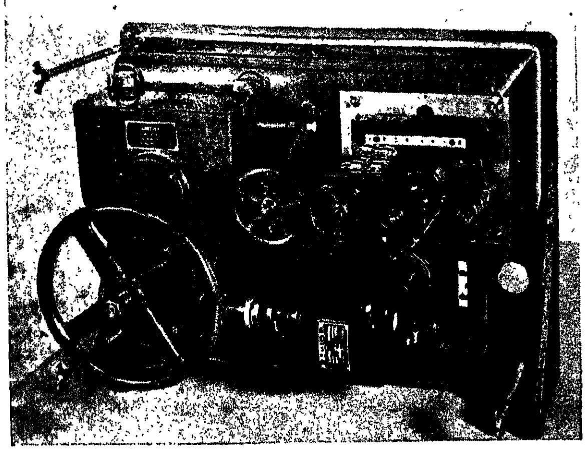

Fig. 11—Drive Unit—Leeds and Northrup

Bailey System. The master steam pressure contactor located at *M*, Fig. 1, is actuated by changes in steam pressure. Each boiler drum switch is energized by a "more" or "less" contactor depending upon the load demands. Each boiler drum switch *A*, then causes its control units, the induced draft regulator *B*, the forced draft regulator *D*, and the fuel feed regulator *E*, to respond in the direction indicated by the master contactor. A continuously rotating cam causes the impulses to be sent out once each revolution. The speed of the cam is adjusted to suit individual requirements. Each regulator, controlled by the boiler drum switch, is changed in steps until the pressure is again normal. The forced draft regulator *D* is also readjusted automatically by the furnace pressure regulator *C* so as to maintain constant furnace pressure or vary it with the load. Static pressure existing inside the furnace is obtained by a small pipe through the boiler wall at C_1. The air or fuel supply to each individual boiler is readjusted automatically to maintain the proper relation between them and is accomplished by using the steam-flow-air-flow relation of the Bailey boiler meter *K* as an indication of the amount of excess air being used for combustion. The steam-flow-air-flow contactor is illustrated in Fig. 7. Impulses received at the control drive cause the various units to operate in steps and thus eliminate any hunting effects. Response to sudden load changes is inherently slow. A modern control panel is illustrated in Fig. 6.

The control drive (Fig. 1—*B*, *D*, and *E*) consists of a continuously running motor driving a system of gears which advances or retards the equipment to be controlled in response to the impulse sent out by the contactor or push-button.

In pulverized fuel or oil burning installations, the control drives are interlocked, so that when the maximum capacity of the air supply has been reached an interlock prevents any additional fuel from being supplied and when the fuel supply has been reduced to its lowest limit an interlock prevents the air from being further reduced.

Enco System. The master controller shown at *A*, Fig. 2, is a steam pressure regulator of the weighted diaphram type and controls the amount of air supplied to the boiler by regulating (through regulator *D*) the forced draft fan speed *H* or its dampers in steps until normal steam pressure is again restored. This device is illustrated in Fig. 8. Both forced draft and fuel may be directly controlled if required.

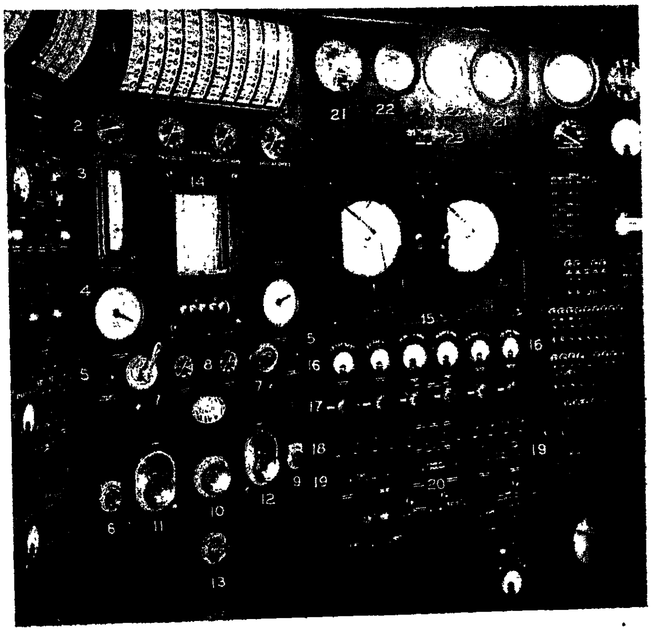

Fig. 12—Control Panel—Smoot System

1. Draft gages
2. Air and oil gages
3. Drum water level indicator
4. Position indicator—feed water check valve
5. Control—feed valve
6. Air supply valve—manual control
7. Transfer valves—manual or automatic
8. Gages for equalizing air supply to boiler master when transferring
9. Air supply valve—automatic control
10. Manual master rating control
11. Maximum rating control
12. Minimum rating control
13. Magnetic transfer valve for fuel feed—motor-generator set
14. Boiler master
15. Voltmeters for generators supplying fuel feeder motors
16. Fan speed indicators
17. Transfer switches—manual or automatic control of fans
18. Solenoid operated transfer indicators
19. Manual control for fans
20. Manual control for fuel feed
21. Steam pressure gage
22. Steam pressure gage—forced draft fans
23. Emergency trip—air and fuel supply

The furnace pressure is maintained at a constant value by a balanced draft furnace pressure regulator *C* which by means of a damper regulator unit *B* controls the induced draft fan or its damper G and the fuel feeder speed E. A furnace pressure regulator is installed on each boiler. Static furnace pressure is supplied by a pipe through the furnace wall.

One steam pressure regulator may be used to control any number of boilers or groups of boilers, or two or more steam regulators may be used for large installations.

An electrical sending and receiving unit, Fig. 9, is available for large installations and provides master control for any number of units from a central point. This equipment provides for almost any combination of control for the combustion process. Each boiler can be controlled as a unit or any number of boilers can be controlled automatically as a group from a master switch.

This method of combustion control can be provided with hydraulically or electrically operated equipment and in either case the equipment can be adjusted so as to keep the load on the various boilers within their minimum or maximum limits.

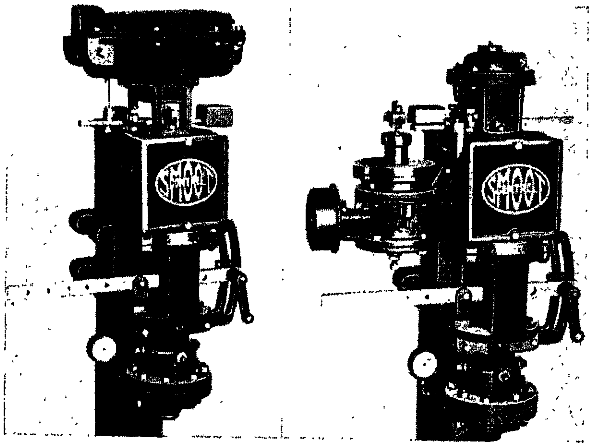

FIG. 13—REGULATORS—SMOOT

A. Standard regulator B. Speed regulator

Leeds and Northrup System. A master electric control current is varied in response to changes in steam pressure by means of a master controller automatic rheostat located at M, Fig. 3. The master control panel is illustrated in Fig. 10. The control current is supplied to the controllers on each of the boilers through the individual boiler panel A where the amount of current supply for each boiler is regulated by a rheostat. The control current is then balanced against the metered rates of fuel and air supply for each boiler at controllers K, C, and E. Contacts on these controllers control the rate of speed of the drive units B, D, F. The drive unit is illustrated in Fig. 11. Differential furnace pressure drop measured at R and R_1 is balanced against the control current in the air-flow controller. Piping through the furnace wall brings the static pressure to the furnace pressure controller where it also is balanced against the control current. However, for the fuel feed controller no natural balancing pressure exists but one is obtained mechanically by means of a blower located at T. The pressure thus produced is proportional to the feeder motor speed.

Irregular action of the fuel feeders or quality of fuel may be corrected by fuel feed compensators controlled by a fuel-air ratio rheostat. These devices are not shown. They readjust the fuel feeder speed.

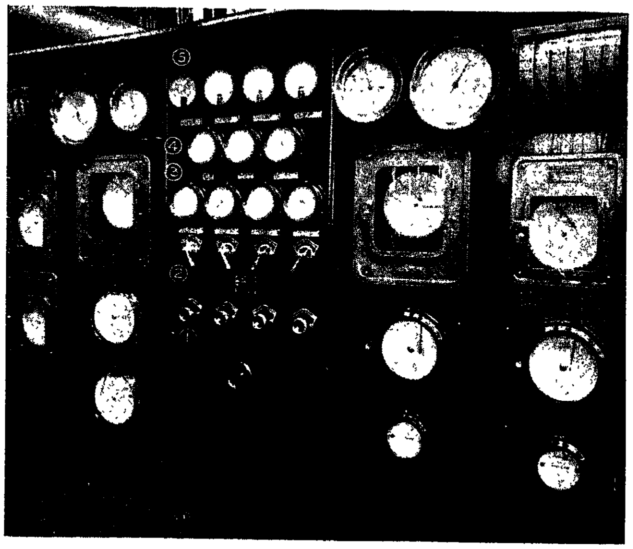

FIG. 14—CONTROL PANEL—HAGAN

1. Impulse relay between sending and receiving unit for modifying impulse
2. Selector switch (manual or automatic)
3. Impulse indicators—fuel and draft
4. Air, loading and 60-lb. air gages
5. Ammeters for motors on fuel pulverizing equipment

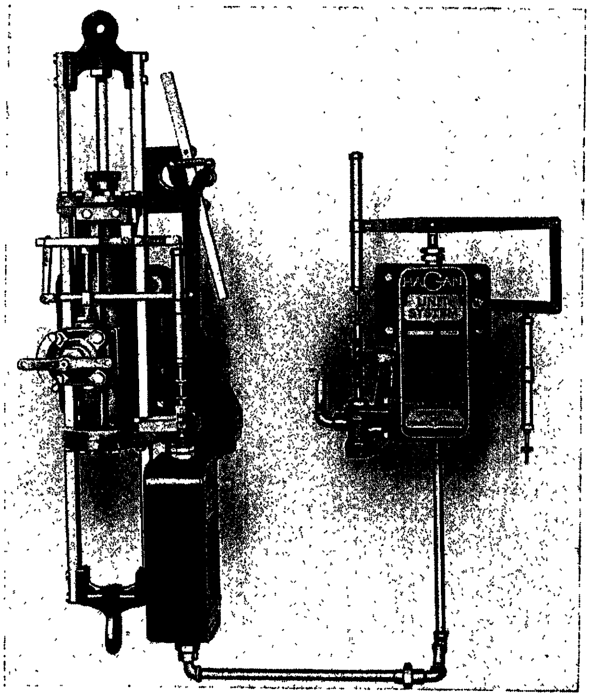

FIG. 15—PRIMARY CONTROLLER—HAGAN

If the control, relay or motor circuit fails, an alarm sounds and the power is automatically cut off the drive units.

Smoot System. The master controller M, Fig. 4, in response to steam demands, regulates the pressure on air loading lines which are connected to boiler masters B on each boiler. From each boiler master there are air loading lines to regulators (at B, D, and E) which directly control the induced draft fan or dampers G, the forced draft fan or dampers H, and the fuel feed motors F. A typical control panel for a large installation is illustrated in Fig. 12. Each regulator (Fig. 13) is balanced against an air loading line and the force which it controls by means of a checking diaphram which is part of the regulator. Pressure at C_1 is a measure of furnace pressure, and at S is a measure of air flow.

The checking diaphram of the regulator controlling the fuel feeder speed is provided with a self-contained speed governor, the speed of which is proportional to the feeder motor speed. Thus, the master loading pressure determines the value of the pressure, draft, or speed which is furnished at any instant. Any changes in steam pressure are rapidly transmitted to all regulators through the master controller and boiler master. By adjusting the valves in the air loading lines from the master controller M the load can be divided among the boilers as desired. The proportion of fuel and air supplied to any boiler can be varied by adjustment of the valves on the air lines from the boiler master. In case constant furnace pressure is desired the furnace pressure regulator is not master loaded but is balanced against a spring.

Hagan System. An element directly responsive to steam pressure is mounted on the panel M, Fig. 5, from which a pneumatic impulse is transmitted to the several boilers under control. The air in the system is maintained at approximately 60 lb. pressure. The proportion between the impulse and the steam pressure may be varied in the field. There is one boiler panel A (illustrated in Fig. 14) per boiler on which are mounted compensating relays by which manual control or a modification of the impulse to (and hence the loading of) that boiler may be obtained. A sending and receiving unit is illustrated in Fig. 15. The impulse is transmitted to the induced draft regulator B and balanced against the draft taken at a given point such as S. The regulator B is of the mercury sealed balanced float type.

A balanced furnace pressure (subject to manual modification or control) is maintained by the regulation of the forced draft fan speed H (and damper H_1). A balanced float controller, C, of the varying impulse type, responds to the furnace pressure and originates an impulse which is sent to the forced draft fan regulator D and to damper regulator D_1, which adjusts the speed of the fans H and damper position H_1. The normal forced draft may be adjusted from the boiler panel as desired.

The gas flow through the boiler is thus established and is measured by means of the pressure drop across the economizer at R and R_1.

In order to determine the rate of coal admission, two pressure connections R and R_1 are taken to a coal feed controller E, of the balanced float type, which is provided with a mechanism for adjusting the ratio of impulse to air flow. This impulse is then taken to the boiler control panel, modified as desired, and then transmitted to the coal feeder regulator F which adjusts the fuel feeder motor F_1.

A control for double boilers, having the following additional features is available:

1. Speed of each induced and forced draft fan can be adjusted separately at the drum controller.
2. Impulses from each coal feeder regulator are totalized before being sent to the coal feeder regulator.
3. Forced draft dampers may be adjusted from the boiler panel independently as furnace conditions require. This is of special value in pulverized fuel installations where the air resistance or flame shape may be abnormal.

CONCLUSION

The question is often asked, what financial return may be expected from an investment in automatic combustion control? The answer is infinitely more involved than the question.

Savings in operating expense as high as 4 per cent have been reported. Rarely, however, has it been found practicable to make comparative efficiency tests on the same installation, operating with and without automatic control, to determine definitely, the annual saving in operating expense.

As a rule, automatic control is seldom installed on the sole basis of a direct saving in operating expense. In fact its installation is often based mainly on resultant operating advantages otherwise difficult or even impossible of accomplishment. Among the more important of these advantages are:

The uniform loading of all boiler units.

Instant response to changes in load.

The supply of fuel and air in correct proportions at all times.

A ready means of providing for safety of operation through sequence interlocking of auxiliary equipment.

Discussion

I. Melville Stein: Referring to the statement at the bottom of the first column on page 1379, which refers to poor steam pressure regulation obtained with the older forms of "on and off" regulators, it is not altogether correct to charge these older forms of regulators with producing poor pressure regulation because some of them produced very good pressure regulation. They were defective, however, in that the good pressure chart was obtained at the expense of very large changes in the draft, the result being that the air flow was always too large or too small, and either condition resulted in large losses in combustion efficiency. Of course, if these regulators functioned by changing the speed of a steam engine driving a fan instead of being directly connected to a damper, poor pressure regulation may have resulted, due to the lag in the response of the engine, but this defect is not properly chargeable to the regulator.

On page 1380, the authors point out that automatic controls can be arranged satisfactorily to regulate rather complex installations. While this is strictly true, I should like to make a plea that installations be kept as simple as possible, rather than to follow the tendency to make them complicated just because automatic controls can handle complicated installations. In this connection, the station auxiliaries involved in the automatic control of combustion could be designed or selected with the requirements of automatic combustion control fully in mind. It cannot be expected that the best automatic control installation can be made if these auxiliaries are designed just as they were prior to the advent of automatic combustion control. As specific examples of the design of auxiliaries which cause trouble in applying automatic combustion control are the use of drum controllers on the motors of the draft fans which have too few steps and the use of stokers requiring a gear change in order to cover the operating range of capacity.

With reference to the use of interlocks, as discussed on page 1382, it should be mentioned that in installations employing two or more unit mills per boiler, an additional interlock should be provided to prevent increasing the air supply beyond the upper limit of fuel capacity when one or more of the mills is out of service.

In connection with electrical systems of control, I should like to point out that the type of drive unit usually supplied and shown typically in Fig. 11 of the paper is self-locking in the event of the failure of power supply; in other words, an unbalanced damper cannot drift to the full open or full closed position, but is held by the drive unit in the particular position which it has at the moment the power supply fails.

An advantage of automatic combustion control which is not mentioned in the paper is its ability to show up operating difficulties, such as defective baffles, etc., before they would otherwise be detected. Under automatic control, the steaming rate of all boilers is stabilized, and if a particular boiler shows an erratic steaming rate, it will, in most cases, be found that some defective condition of the boiler or firing equipment is developing. The defect is thus anticipated before it causes any real disturbance.

T. G. Robinson: Some very satisfactory experience has been obtained with the Leeds & Northrup Company's system of automatic combustion control (State Line) and also that manufactured by the Bailey Meter Company (Powerton) and the Smoot Engineering Corporation (Waukegan). In two of these installations, automatic control was used in connection with two and three speed induction motors on the draft fans. While satisfactory performance was had with both installations, there has been of late a desire to eliminate multi-speed induction motors with the inherent complications in speed changing switches and damper coordination problems. This led to the application of variable speed Rossman drives for draft fans.[1]

On a recent extension to one station, where three-speed induction motors were formerly used, the general boiler control scheme was simplified considerably, due primarily to employing Rossman drives on the draft fans. The Bailey Meter Company's standard steam-flow-air-flow, and furnace pressure automatic controllers were used in connection with the Rossman simplified scheme of automatic control. With this control the standard Bailey drive units were not employed; instead, the electric impulses from the several automatic controllers were sent direct to the pilot motors on the rheostats for the adjustable-speed fuel feeder motors and speed regulating rheostats for the Rossman drives.

Recently a number of tests was performed on this installation for the purpose of determining the general performance of the automatic control system. The results not only indicated reliable operation, but satisfactory performance as regards its ability to maintain steam pressure, steam production, draft conditions, and over-all combustion efficiency. One very interesting test was made to see if the steam-flow-air-flow automatic controller might not be eliminated by depending on the relation between the time of travel of the speed regulating devices for the induced draft fan and fuel feeder motors. In this test only the furnace pressure automatic controller was used. This was employed to vary the speed of the forced draft fan to maintain automatically the predetermined furnace pressure. Results of the test showed that the steam-flow-air-flow automatic controller was necessary to maintain combustion efficiency, but indicated some promising possibilities in respect to coordinating the time of travel of the several speed regulating devices.

With reference to the authors' mention of interlocking sequences, we would like to point out an interesting application in connection with a recent boiler installation (Philo). Time delay relays were used, in the safety interlocking of the boiler auxiliaries, ranging from thirty seconds up to as high as two minutes. These were employed in the normal shutting down procedure between the pulverizer mill exhausters and the draft fans for the purpose of emptying the pulverizer mill and cleaning out the fuel conduits to the furnace, and to remove the gases of combustion.

We would point out that recent tests and analysis of one boiler installation in the Chicago area (Calumet), indicated an over-all increase in efficiency of approximately 4 per cent which corroborates the statement in the conclusion of the paper. There seems to be a need for more economic studies of this nature on automatic combustion control systems. Of course, as the authors mention, the results will vary with each particular installation. Although it is quite a difficult and tedious matter to integrate the savings due to the complex aggregation of variables in boiler installations and operation, some steps should be taken to tabulate the results of each particular installation in order to secure a clearer economical aspect of the situation.

T. A. Peebles: The statement "That if an operating force is sufficient in numbers, highly skilled, and supplied with adequate instruments results can be obtained with a well planned manual control which compare favorably with the best automatic control," brings to mind a large industrial plant of six units burning two different fuels. This plant is operated under automatic control with two men on the firing floor and securing the same results which the superintendent states could be secured with a manual control system operated by twelve men. It would be possible to recruit and train the required ten extra men per shift or thirty in all, but the turn-over would be large because the training these men would receive would fit them for something better. A plant operated in this manner would be in effect a training school in which young engineers would spend a comparatively short time as a preparation for advancement, but no one employer could hope to absorb into other departments the number of men who would become available.

In a large central station, an eighteen-month study of the relative merits of manual and automatic control convinced the management that in the operation of large boiler units, there are certain adjustments which can be made by machinery to better advantage than by hand; an automatic control was installed.

However, automatic control does not completely take the place of operative skill. Being machines, the control devices can do only those things put into them by the designer, who of necessity makes certain assumptions which are not always correct. As pointed out by the authors, the changing condition of the gas passages and variations in fuel introduce errors requiring manual adjustment. Even the steam-flow meter cannot always be depended upon to show the true condition, because the steam flow is a measure of what a boiler is doing only when the pressure is kept practically uniform and the flow of water to the boiler is proportional to the steam flow. All these variables combine to produce a condition that calls for continuous attention on the part of a skilled operator, but since automatic controls take care of all adjustments required to meet varying loads and maintain desired draft conditions, the operator's work is greatly simplified. Experience and judgment are required to interpret the indications of the boiler instruments and make the correct adjustments, but one skilled operator aided by an automatic control can burn a lot of fuel and burn it efficiently.

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[1] *A New System of Speed Control for A-C. Motors,* by A. M. Rossman, Trans., A. I. E. E., March 1931, p. 162.

Engineers considering the use of automatic control should keep in mind the authors' statement that the cost of a remote manual control system represents a large proportion of the cost of a complete automatic control. The manual controls must be grouped on suitable panels with indicators which enable the operator to determine at a glance the settings of the various control devices, and each valve, damper or rheostat requires a power unit for its operation. Such a system represents a large proportion of a complete automatic control. If the cost of manual control and the things it can do are carefully compared with the cost and performance of a complete automatic control, it will be found that substantial operating advantages may be secured at surprisingly low cost.

Three Years' Operating Experience with Miniature Switchboard Supervisory Automatic Control

BY R. M. STANLEY[1]
Fellow, A. I. E. E.

INTRODUCTION

THE Ohio Falls Hydroelectric Station at Louisville, Kentucky, contains eight hydroelectric units, each having capacity of 13,500 hp. at 37 ft. head. The generator room is 44 ft. wide and 508 ft. long. The waterwheels are 5-blade propeller type axial flow runner, developing the rated horsepower at a speed of 100 r. p. m. This type of wheel was selected because of its ability to operate under a range of heads varying from the maximum of 37 ft. down to 8 ft. Each generating unit is complete in itself. Waterwheel, generator, exciter, governor, electrical control, oil and water supply, oil circuit breakers, etc., are individual to each generating unit and all related unit auxiliaries are fed entirely from that unit.

A hydraulic control unit and an automatic electrical control unit are located near each generating unit. The electrical control equipment is similar to that used in all stations but in each case is placed inside of a sheet steel cubicle located adjacent to the governor.

There is a centralized supervisory control miniature switchboard located in about the center of the plant with a multi-conductor telephone cable between the miniature board and each generator control unit. The miniature switchboard is illustrated in Fig. 1. The generator switchboard—front view—in its steel cubicle is shown in Fig. 2; rear view—Fig. 3. A one-line diagram of the station generating and transmission buses and the 230-volt unit and station auxiliary buses is shown in Fig. 4.

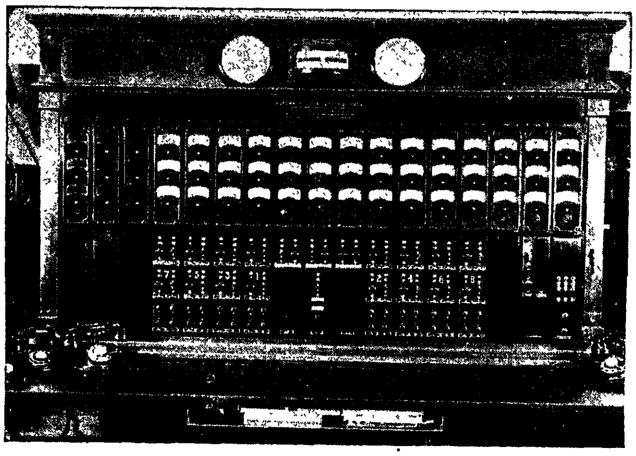

FIG. 1—MINIATURE SWITCHBOARD

A description of the engineering and construction features of this installation may be found in a paper by R. M. Stanley and E. D. Wood, A. I. E. E. TRANS., March 1931, page 370.

MINIATURE SUPERVISORY SWITCHBOARD

The miniature supervisory board in some respects resembles a manually operated telephone switchboard. The arrangement of control keys and indicating instruments on 4-inch panels places the control of all generators, transformer banks, etc., within convenient reach. The operator sits at this board with all of the panels, controlling load, reactive voltamperes and voltage conditions of all generators within a distance of 2½ ft. This results in closer supervision of generating apparatus at the hydro, in better loading of machines, and better frequency regulation at such times when regulation is passed to the hydro.

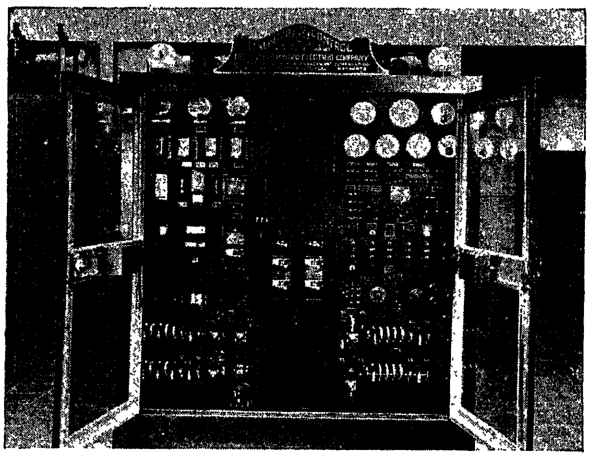

FIG. 2—GENERATOR SWITCHBOARD, FRONT VIEW

Aside from convenience and closer supervision there is another distinct advantage, namely, time is saved in performing operations when the plant is most needed and the item "human error" is controlled to a large extent. There is a considerable saving in labor cost since only one operator is needed per shift, the yearly cost being 9,500 man-hours for three operators per twenty-four hours, including the relief operator. Apt young men of limited experience are entirely satisfactory for supervisory operators in this station.

The time saved in putting machines on the bus is especially important during system disturbances and it is possible, when urgently needed, to bring a 13,500-hp. hydro generator unit up to proper speed and put it on the bus in one minute. Additional units can be put on in approximately thirty-second intervals thereafter.

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[1] Elec. Engr., Byllesby Engg. & Management Corp., Chicago, Ill.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

Due to the speed with which units can be put on the bus at the hydro, it has become the practise to carry less reserve steam capacity when units are available at the hydro.

MAINTENANCE

The miniature board is no more costly to maintain than any other type of switchboard. In fact, a comparison of maintenance costs on a benchboard and vertical board with full sized instruments, control switches, etc., at Waterside Steam Station indicates that the maintenance cost and inspection of the miniature switchboard and automatic equipment is less. With the exception of the instruments, the board is made up of equipment similar to telephone equipment. Multi-conductor, lead-covered, telephone cable is used to connect this miniature board with the individual control panels associated with each generator. The performance records of the miniature supervisory board for the years 1928, 1929, and 1930 are given in tables at the end of this paper. This record shows the type of equipment associated with the miniature supervisory board, the approximate number of operations and the number of failures.

There is very little cleaning to be done, the equipment being enclosed in a practically dust-proof cabinet. There is some small maintenance of the board such as cleaning control keys, contacts, etc., and renewing miniature lamps. The major portion of technical service required has been in the nature of checking and testing out new equipment. In general, it may be said that once the equipment has been properly installed and adjusted, it remains so without constant maintenance.

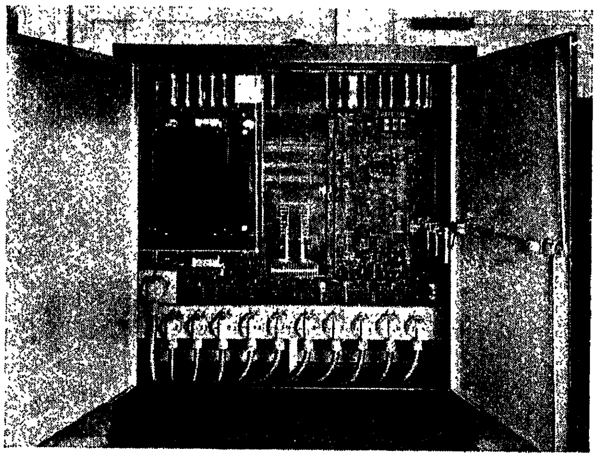

FIG. 3—GENERATOR SWITCHBOARD, REAR VIEW

GENERAL SCHEME OF CONTROL

The general scheme of control is that the turning of a miniature control key at the miniature supervisory board sets into operation automatic relays associated with the unit being supervised. These automatic relays function in a predetermined sequence with the starting of generator, shutting down of generator, or making alive a transformer bank and synchronizing same with another system. Remote indication of the kilowatt load, reactive voltamperes and voltage on each generator is given on miniature instruments by direct connection through No. 19 gage, multi-conductor telephone cable to 1/1 insulating transformers and 5/0.5 ampere current transformers. Indication of load, reactive voltamperes and voltage on transformer banks is given by means of Selsyn type miniature instruments on the miniature supervisory board. A brief outline of what takes place when a supervisory operator starts a unit will make clear where time and labor are saved in the control of this station.

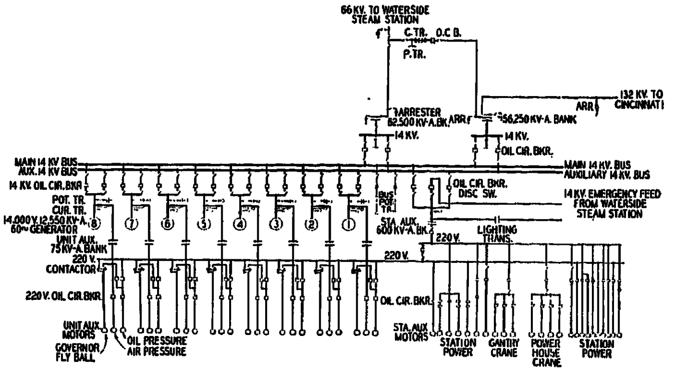

FIG. 4—ONE-LINE DIAGRAM OF GENERATING STATION AND TRANSFORMER BUSES AND 230-VOLT UNIT AND STATION AUXILIARY BUSES

1. Supervisory operator turns a key which selects the bus and synchronizing method.
2. Supervisory operator pushes button which gives starting impulse to the following operations:
   - Governor oil pressure automatically maintained at all times.
   - Brakes release automatically.
   - Gates open to predetermined setting.
   - Field applied automatically.
   - Governor fly-ball motor transfers automatically from station supply to generator supply.
   - Generator air cooling water system starts automatically.
   - Machine synchronized automatically to bus selected.
3. Supervisory operator regulates load, voltage, and reactive voltamperes.

Shutting Down a Unit

1. Supervisory operator backs down load.
2. Supervisory operator gives stop impulse.
   - Line breaker opens automatically.
   - Field removed automatically.
   - Gates closed automatically.
   - Brakes applied automatically.

Protective Equipment which Replaces Watch Operator

Four bearing temperature relays.
One water-cooling relay.
One overvoltage relay.
One governor low oil-pressure relay.
Generator differential relays.
Loss-of-field relay.

From the foregoing it is evident that the automatic equipment is used extensively to replace manual operating duties. During 1928 (the first year the plant was operated) it was customary to test this equipment out completely every week because of the relative novelty of the installation. During 1929 tests were made monthly and now the equipment is tested only at intervals of three or four months when it appears to be necessary to clean the equipment.

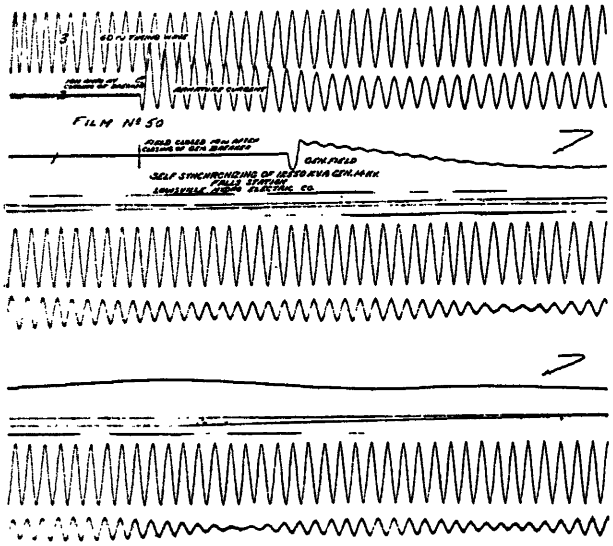

Fig. 5—Self-Synchronizing of a 12,550-Kva. Generator—14 Kv.

Generators may be synchronized to the bus by two methods; first, through self-synchronizing equipment wherein the machine is brought up to speed, the armature is closed in on the bus and the field applied instantly thereafter. Second, automatic synchronizing relays may be used which closely approximate the manual method of synchronizing, that is, the speed of the incoming machine is regulated to match that of the running machine and, when the phase angle between the voltage of the two machines is satisfactory, the machine is closed in on the bus. Each method has its advantages. The self-synchronizing method is faster, requiring about one minute to bring a machine up to speed and synchronize. This method is generally used when the system capacity is large and the head of the river is above 20 ft. It has a distinct advantage over automatic synchronizing in that, during periods of severe system trouble when the frequency starts going down due to loss of generator capacity, it is possible to self-synchronize a unit and have it pull in step with this lower frequency. From oscillograms made at the plant (see Figs. 5, 6, and 7) the current taken by the armature varies from one and one-half to twice normal. This dies down rapidly and generally reaches normal value in ten cycles and there is a slight dip in system voltage at the Waterside Steam Station equivalent to about one volt on 110-volt basis. The automatic synchronizing equipment is used when the output of the hydro is small due to low head. Synchronizing takes longer but is very exact. The majority of the synchronizing operations with this equipment requires from two to three minutes from the time the unit is started.

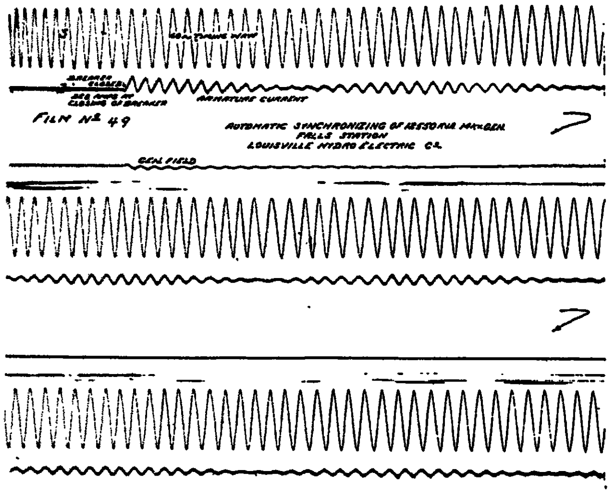

Fig. 6—Automatic Synchronizing of 12,550-Kva. Generator—14 Kv.

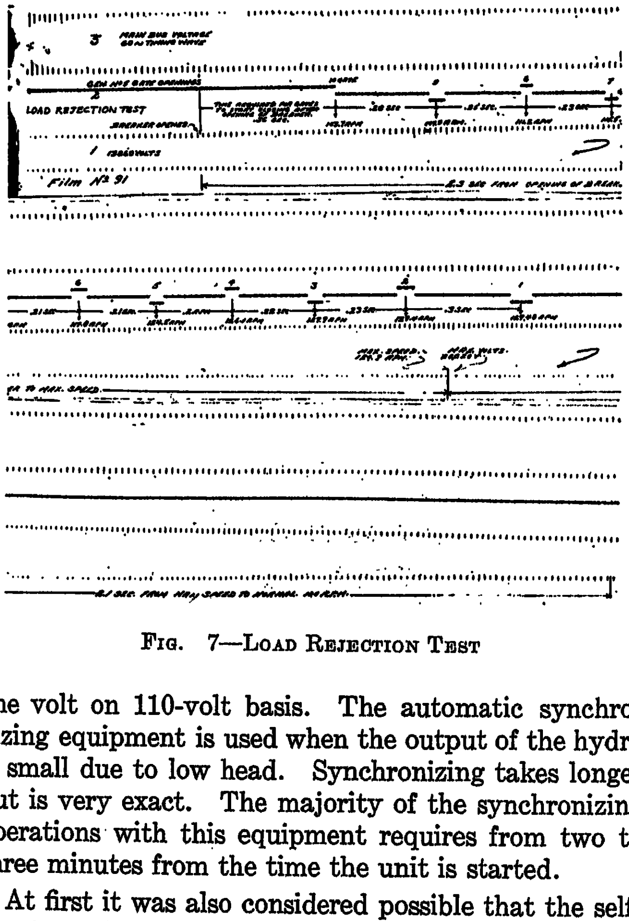

Fig. 7—Load Rejection Test

At first it was also considered possible that the self-synchronizing method might not be satisfactory due to the "bump" given the system when closing the generator oil circuit breaker and only one machine was thus equipped. However, subsequent operation of the waterwheels has been so satisfactory that the other seven machines have been equipped with self-synchronizing equipment and this method is used whenever it is considered desirable, as outlined in the foregoing, and the self-synchronizing method is now considered preferable.

TABLE I—TABULATION OF DISTURBANCES

	No. 1	No. 2	No. 3	No. 4	No. 5
Cause of disturbances	Lightning tie line	Lightning tie line	Lightning 13-kv. feeder	Lightning tie line	Trans. failure
Outages—tie lines relayed	Yes	Yes	Yes	Yes	High & low O. C. B.
Generators on bus	8	5	1	2	2
Generators shut down by dist.	8	5	1	2	2
Load on station	60,000	27,500	6,000	16,800	8,500
Load dropped	60,000	27,500	6,000	16,800	8,500
Performance of Automatic Equipment					
Generator overvoltage relay	Operated to shut down unit (same as No. 1)				
Master control circuit interrupted	Automatically				
Generator oil circuit breaker	Opened automatically				
Generator field	Removed automatically				
Governor solenoid	Deenergized				
Waterwheel gates	Closed automatically				
Brakes	Applied automatically				
Supervisory indicating lights	O. K.				
Supervisory generator control key	Turned manually				
Station aux. supply transferred	Automatically to emergency source				
Station power and lights	O. K.				
Restoring Service					
Tie lines oil circuit breakers	Closed from supervisory board				
Generator starting impulse	Given by supervisory operator				
Master circuit complete	Through starting impulse				
Governor solenoid	Energized automatically				
Brake released	Automatically				
Waterwheel gates opened	Automatically				
No. of generators syn. manually	4	2			1
No. of generators automatic	4	3	1		
First generator on bus in	2 min.	3 min.		On only ½ min.	
Last generator on bus in	4 min.	4 min.	3½ min.	Trouble still on line	

Reference is made to Table I which gives the performance record of equipment associated with supervisory control. The first item—telephone cable—consists of lead-covered No. 19 gage, double paper insulated telephone cable. Impulses are sent from the supervisory board over this cable to the generator cubicles located near each generator. Relays located in the cubicle receive the impulse and set automatic equipment into service. Supervisory impulse current varies from 0.2 to 0.5 ampere, the voltage impressed being either 60 or 125 volts direct current.

Over a period of three years there have been no failures in the cable conductors. Each one of the multi-conductor, lead-covered telephone cables has a few spare conductors so that failures can be taken care of readily and the system can be expanded if desired. Push-buttons used for control of load and voltage are similar in construction to telephone jacks; spring contacts complete the circuit to the generator cubicle where small contactors operate to regulate frequency or voltage. Rotating type keys, similar to telephone equipment, are used for giving the starting impulse, for selecting the bus to which the generator is to be synchronized, either main or auxiliary, for selecting the method of synchronizing, either automatic or self, and for opening or closing oil circuit breakers. Fig. 8 shows the appearance of the keys. The number of operations shown in Table II has been estimated from the total machine hours which are recorded in the station log.

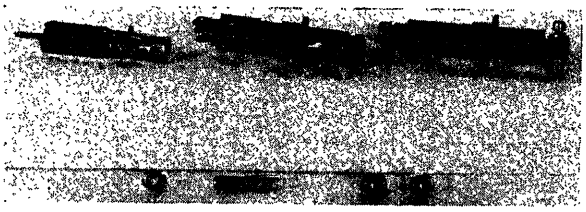

FIG. 8—APPEARANCE OF KEYS

A few cases of trouble were experienced and traced to insufficient spring tension. Thereafter the spring tension was adjusted on all keys and no more failures have occurred. Three telephone lamps give the supervisory operator an indication of the position of the equipment; green for deenergized, red for energized, and white indicating that the position of the control key does not agree with the position of the equipment. Thus, during an outage, the green and white lamps appear, showing that the equipment has taken an open position. The supervisory operator then turns the control key to the open position which extinguishes the white lamp, leaving the green lamp burning. Polarized relays receive the supervisory impulse originating from the rotating type keys on the miniature board. These keys being 2-position keys give an energized signal or a deenergized signal to the polarized relays. The armature of the relay, in turn, moves to the energized or deenergized position. These relays function, (1) to open or close the master control contactor; (2) complete the circuit for the method of synchronizing selected—either automatic or self; (3) give to the synchronizing equipment the control of the generator breaker selected—either main or auxiliary; also complete the circuit for lamp indication.

Throughout the years of service shown on the tabulation, there has been only one case of trouble which was somewhat unusual. This trouble developed when relays were subjected in summer to an ambient temperature of 50 deg. cent. and the compound with which the coils were impregnated tended to vaporize and deposit on the armature, causing sticking in one position. This type of coil was changed and no further trouble experienced. A glass cover makes this relay practically dust-proof and very little maintenance is required.

TABLE II—SUPERVISORY BOARD PERFORMANCE RECORD

No. in service	Equipment	Operations per year	Failures	Trouble chg. to Manufacturer	Trouble chg. to operation	Year
	3,000 ft. of telephone cable				No trouble	1928
						1929
						1930
39	Push-button control load & voltage	80,000	2	None	2	1928
		90,000	2	"	2	1929
		74,000	None	"	None	1930
37	Telephone type control keys	6,022	2	2	None	1928
		5,500	10	None	10	1929
		4,750	None	"	None	1930
78	Polarized telephone relays	9,948	30	30	None	1928
		8,300	5	5	"	1929
		7,590	None	None	"	1930
32	Voltage & load control contactors	80,000	None	None	None	1928
		90,000	"	"	"	1929
		74,000	"	"	"	1930
24	Generator meters, kv., kw. & r.kva	122,676 hr.	% accuracy	2	None	1928
		136,245 hr.	of full	2	"	1929
		101,715 hr.	Scale 1%	None	"	1930
7	Selsyn meter, kv., kw. & r.kva	33,728 hr.	% accuracy	None	None	1928
		25,888 hr.	of full	"	"	1929
		29.712 hr.	Scale 1½%	"	"	1930

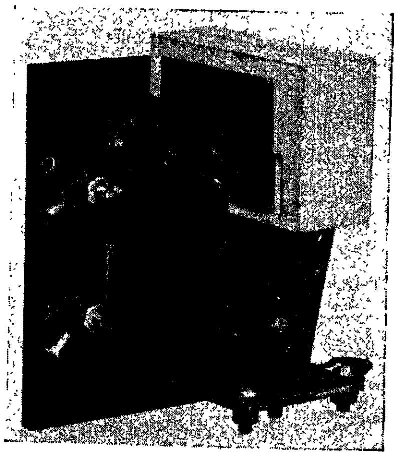

FIG. 9—TYPE OF CONTACTOR

Fig. 9 shows the type of contactor used for load and voltage control. These contactors are energized directly from the push-button key on the supervisory board; there has been no trouble experienced. The miniature supervisory switchboard instruments are approximately half the size of typical benchboard instruments, the scale deflection being 3 inches. These meters can be read sufficiently accurately for all practical purposes. The generator meters are calibrated to divisions of 500 kw. while the transformer instruments are calibrated in divisions of 3,000 kw.

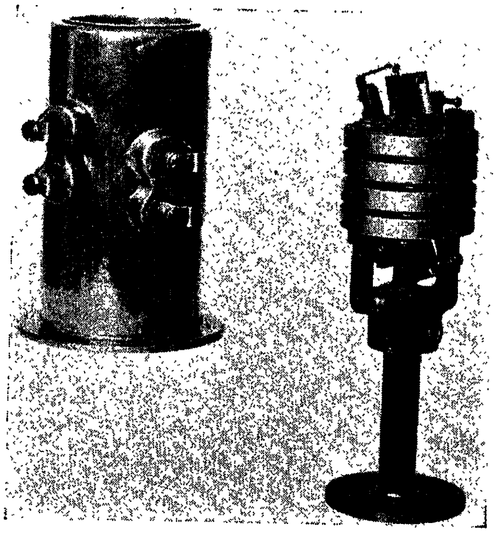

FIG. 10—OVERSPEED DEVICE NO. 12

GENERATOR PROTECTIVE EQUIPMENT

Overspeed Device No. 12. The overspeed device (Fig. 10) is centrifugally operated and is direct-connected to the shaft of the unit, being mounted above the exciter which in turn is above the generator. This device is similar to those used in many other hydro plants. A speed of 131½ r. p. m. for operation of this unit is selected as being sufficiently above the speed of 127 r. p. m. which the unit attains when full rated load is rejected. A unit shutdown does not take place in case of momentary rises in speed but only in case of sustained overspeed due to improper governor action.

Overvoltage Relay—Device No. 59. An induction type relay which functions to shut the machine down on a sustained voltage of 16,500 volts, normal generating voltage being 14,000 volts, functions in 0.8 of a second and, as it operates on an inverse time characteristic curve, voltages of higher magnitude will cause the relay to function in less time. This device only functions to shut the unit down in case the generator is tied in on the bus so that, in case of overvoltage resulting from the generator oil circuit breaker opening and dropping all the load, the unit will not be shut down unnecessarily.

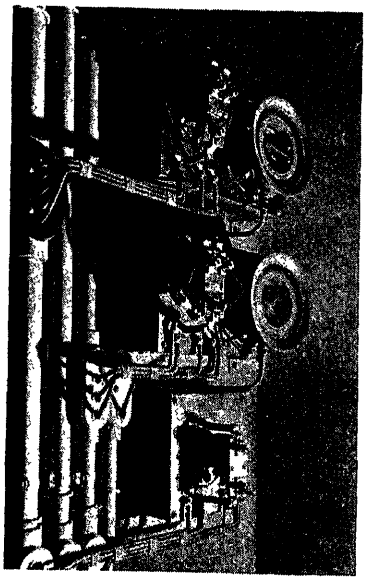

FIG. 11—GOVERNOR OIL-PRESSURE RELAYS—DEVICE NO. 63

Governor Oil-Pressure Relay—Device No. 63. The governor oil-pressure regulating gages and relays are shown in Fig. 11. The upper or *A* gage holds the oil pressure between 145 and 165 lb. by starting and stopping the oil-pressure pump electric motor while the generating unit is shut down. When the generating unit is started up, a pilot relay causes the oil-pressure pump to run continuously, oil pressure being regulated by means of a by-pass regulating valve which holds the oil pressure between 155 and 175 lb. The *B* gage functions an auxiliary relay to shut the unit down in case the oil pressure should drop to 135 lb. The hand reset on this device will not hold in until the pressure is 140 lb.

Generator Phase Unbalance Relay—Device No. 51 G. The device consists of a low-current, inverse time characteristic induction-type relay connected in the generator current transformer neutral.

Lignum Vitae Bearing Cooling Water Relay. To protect the lignum-vitae thrust bearing from damage due to failure of water supply, a contact closing device—normally held open by flow of water to this bearing—is installed on the water supply line. Water must be flowing to this bearing before the master circuit can be completed and the unit started up and likewise, if the water flow stops while the unit is in operation the master circuit will be interrupted and the unit shut down. Trash collecting in the screen at the entrance to the cooling water supply line has caused this device to function satisfactorily.

Bearing Temperature Relays—Device No. 38. One relay furnished by the generator manufacturer protects the generator bearings. A contact making thermometer (Fig. 12) furnished by the waterwheel manufacturer protects the intermediate guide bearing. Both operate at 55 deg. cent. One operation in 1929 shown in Table IV charged to vibration, was caused by an attendant striking the relay with a dusting mop and causing the relay to jar closed.

Loss of Generator Field Relays Nos. 40, 40-X and 40-Y. This relay is connected in series with the generator field circuit. In case of failure of generator field current, contacts on this relay close, energizing an auxiliary contactor No. 40-Y. This in turn closes contacts of a time delay induction type voltage relay, device No. 40-X, shutting the machine down. Operation of this device in 1928, shown in Table IV, was caused by the operating coil on the main field contactor burning out, interrupting the field circuit.

Ground Protective Relay Device No. 64. An instantaneous hand reset relay with its operating coil completing the connecting circuit between the generator frame and the station ground bus is shown in Fig. 13. The relay shuts the machine down in case of a flashover to the generator frame or the grounding of the generator winding. Operations in 1928 of this device charged to vibration were caused by construction work in progress at that time. In 1929 two operations were caused by an electric welder accidentally passing the welding current through the relay coil.

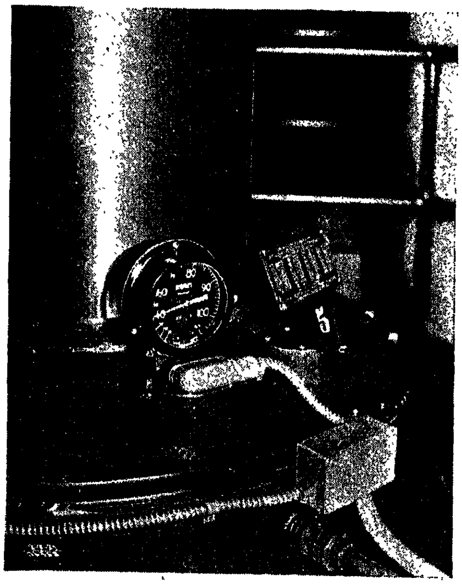

FIG. 12—THERMOMETER TYPE BEARING TEMPERATURE RELAY—DEVICE NO. 38

Differential Relay Protective Equipment Device No. 87.

During 1931 all eight generating units will be equipped with differential relays. As the generators are operated either two-circuit wye or single-circuit delta connection, depending on head conditions, two sets of differential relays will be provided per generator. These relays will shut the unit down in case of a phase-to-phase fault in the generator stator winding.

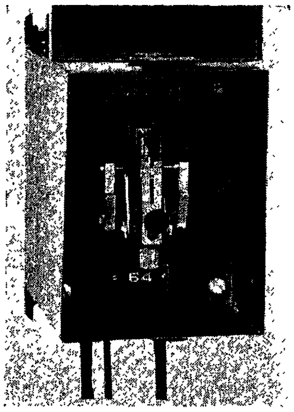

Fig. 13—Grounding Relay—Device No. 64

White and red signal lamps are mounted on top of the generator, the white lamp burning when all temperature relays, ground relays, and loss-of-field relays are normal. If they are not normal, the white lamp is extinguished and the red lamp lights.

TABLE III—PERFORMANCE RECORD OF GENERATING EQUIPMENT

No. in service	Equipment	Oper. per year	Hours in service	Failures	Trouble chg. to			Year
					Mfg.	Eng.	Oper.	
8	Governor oil high-pressure gage relay		40,892	4 relays	Coils	None	None	1928
			45,415	None	None	“	“	1929
			33,905	“	“	“	“	1930
8	Gov. solenoid oper. waterwheel gates	2,966	40,892	None	None	None	None	1928
		2,504	45,415	“	“	“	“	1929
		2,180	33,905	“	“	“	“	1930
8	Gen. field contactor oper	2,966	40,892	1	1 coil	None	None	1928
		2,504	45,415	None	None	“	“	1929
		2,180	33,905	“	“	“	“	1930
8	Gov. fly-ball auto. transfer. sta. aux. to unit aux	1,483	40,892	None	None	None	None	1928
		1,252	45,415	“	“	“	“	1929
		1,090	33,905	“	“	“	“	1930
8	Generator cooling water pump	1,483	40,892	None	None	None	None	1928
		1,252	45,415	“	“	“	“	1929
		1,090	33,905	“	“	“	“	1930
8	Generators put on line	1,483	40,892	1	None	1	None	1928
		1,252	45,415	None	“	None	“	1929
		1,090	33,905	“	“	“	“	1930
8	Generator brake valve solenoid	2,966	40,892	8	None	8	None	1928
		2,504	45,415	6	“	6	“	1929
		2,180	33,905	None	“	None	“	1930

Master Control Circuit and Equipment. In order to start and operate a generator, it is necessary that the master control circuit be a complete electrical circuit from the positive to the negative control bus. This circuit is composed of various devices other than the protective devices which interrupt this circuit either directly or indirectly.

In starting a unit, this master circuit, provided all protective devices are in a normal position, is completed through the master contactor which is energized during the starting process by the supervisory board operator turning the starting control key to the "start" position. The devices which make up this master circuit are listed in Table III. A lock-out hand reset relay operates to interrupt the master circuit when any of the temperature relays, thermometers, ground relay or loss-of-field relay function.

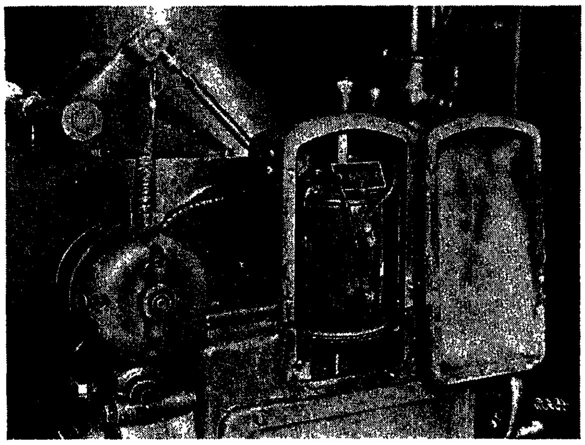

Fig. 14—Governor Pilot Relay Solenoid—Device No. 65-S

Protective devices that interrupt the master circuit directly are the overspeed device and the low governor oil-pressure relay previously described. The protective devices that shut the unit down by indirect operation on the master circuit, other than by means of the lock-out relay, are the overvoltage relay, phase unbalance relay, and differential relays. These last three relays function by short circuiting out the holding-in coil on the master contactor. Deenergizing of the master contactor, in turn, breaks the master circuit, shutting the machine down.

The governor pilot relay solenoid, as shown in Fig. 14 is connected directly in the master control circuit. If the solenoid coil is energized by the completion of the master circuit, a pilot valve is opened on the governor, permitting the governor to function in a normal manner to regulate the waterwheel gates. If this solenoid coil is deenergized, the pilot valve causes the waterwheel gates to close and the generator oil circuit breaker is opened automatically thereafter.

For each generator there is approximately 220 ft. of 19-22 control wire used in making up this master circuit which is protected by the fuses.

A waterwheel gate limit switch (Fig. 15), not a part of the master circuit, functions to complete the tripping circuit to the generator oil circuit breaker, causing this breaker to open when the waterwheel gates have reached a "no load" position and after the master contactor has been deenergized. Differential relays, overvoltage relays, and phase unbalance relays also trip the generator oil circuit breaker and shut the unit

TABLE IV—PERFORMANCE RECORD OF GENERATOR PROTECTIVE EQUIPMENT

No. in service	Equipment	Times oper.	Hr. in service	Operation chg. to:		Year
				Mfg. defect	Protection	
8	Overspeed device No. 12	8	40,892	8 vib.	None	1928
		1	45,415	None	1	1929
		1	33,905	"	1	1930
8	Overvoltage relay device No. 59	3	40,892	None	3	1928
		8	45,415	"	8	1929
		6	33,905	"	6	1930
8	Low governor oil-pressure relay device No. 63	4	40,892	None	4	1928
		1	45,415	"	1	1929
		None	33,905	"	None	1930
8	Phase unbalance relay device No. 51G	None	40,892	None	None	1928
		1	45,415	"	1	1929
		None	33,905	"	None	1930
8	Lignum vitae bearing cooling water relay	3	40,892	None	3	1928
		4	45,415	"	4	1929
		1	33,905	"	1	1930
24	Bearing temperature relay device No. 38	1	40,892	None	1	1928
		1	45,415	1 vib.	None	1929
		None	33,905	None	"	1930
8 each	Loss of gen. field relays devices Nos. 40, 40x, 40y	1	40,892	None	1	1928
		None	45,415	"	None	1929
		"	33,905	"	"	1930
8	Generator ground relays device No. 64	5	40,892	None	5 vib.	1928
		2	45,415	"	2	1929
		None	33,905	"	None	1930

MASTER CONTROL CIRCUIT AND EQUIPMENT

No. in service	Equipment	Hr. in service	Normal oper. start stop	Equipment failure	Shut down due to trouble	Year
8	Master contactor device No. 4	40,892	2,966	None	None	1928
		45,415	2,504	"	"	1929
		33,905	2,180	2 def. coils	"	1930
8	Lock out relay hand reset device No. 81	40,892		None	None	1928
		45,415		"	"	1929
		33,905		"	"	1930
8	Protective devices that interrupt master circuit				22	1928
					18	1929
					8	1930
8	Governor pilot relay solenoid	40,892		None	None	1928
		45,415		"	"	1929
		33,905		"	"	1930
16	D-c. control 30 A	40,892			8	1928
		45,415			None	1929
4	D-c. control 200 A	33,905			"	1930

down regardless of position of the waterwheel gates.

PERFORMANCE DURING SYSTEM DISTURBANCES

To date there have been five system disturbances which resulted in the hydro dropping load. Three cases were due to lightning flashing over on a 66-kv. tie line to the steam plant; one to lightning flashing over on a 13-kv. feeder which is connected to the city distribution system; and one to failure of transformers stepping the voltage up to 66 and 138 kv. Table I indicates the manner in which the units were shut down, the manner in which service was restored and that a very short time was required to get the units back into service and on the bus. These disturbances occurred before the generators were all equipped with self-synchronizing equipment and, therefore, in cases where the automatic synchronizing equipment did not function rapidly enough, the operators put the machines on manually in order to save time.

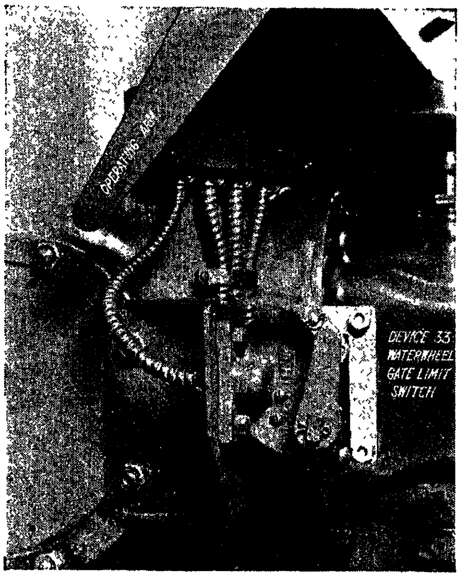

FIG. 15—WATERWHEEL GATE LIMIT SWITCH—DEVICE No. 33

Each disturbance caused a short circuit of considerable magnitude and, when the circuit breakers opened, the overspeed of the generators and consequent rise of voltage was such that the overvoltage protective relays operated, removing generators from the bus and shutting the units down. The bus being dead, the station light and power bank was automatically transferred to the incoming emergency line. It is to be noted that a maximum time of four minutes was required to get the last generator in on the bus in the case of the first two disturbances when, in the first case, eight generators were running and, in the second case, five generators were running. In restoring service, the supervisory operator closes the tie line in on one 13-kv. bus. Thereafter, the starting impulse is given to all generators, automatic means of synchronizing having previously been selected at the miniature supervisory board. As it was necessary to get generators on the bus as soon as possible, it was therefore customary,—previous to the time all units were equipped for self-synchronizing, if the automatic synchronizing equipment had not synchronized the generator promptly enough—for a floor operator to go to each generator cubicle and do so manually. Now that this equipment for self-synchronizing is installed for all generators and, since this method is much quicker, it is being used almost entirely.

CONCLUSIONS

Engineering reasons for adoption of miniature supervisory switchboard control and automatic control were to reduce initial capital expenditure and lower fixed charges. The results of more than three years continuous operation of this equipment show the following:

With the miniature switchboard, the operator is at all times closer to indicating instruments, control switches, etc., and can give better and closer supervision to the

TABLE V—OHIO FALLS HYDROELECTRIC STATION—LOUISVILLE, KENTUCKY PERFORMANCE RECORD OF GENERATOR EQUIPMENT

				Trouble charged to:		
Equipment	Oper. per year	Hours in service	Failures	Mfg. defect	Operation	Years
Generator oil-pressure built up	1,483	45,000	4 Pilot relay	4 Coils burnt out	None	1928
	1,252	45,400	None	None	"	1929
	1,090	34,700	"	"	"	1930
Gov. solenoid operating waterwheel gates	2,966	45,000	None	None	None	1928
	2,504	45,400	"	"	"	1929
	2,180	34,700	"	"	"	1930
Gen. field automatically operated	2,966	45,000	1	1 def. coil	None	1928
	2,504	45,400	None	None	"	1929
	2,180	34,700	"	"	"	1930
Gov. fly-ball auto. transferred sta. aux. to unit aux	1,483	45,000	None	None	None	1928
	1,252	45,400	"	"	"	1929
	1,090	34,700	"	"	"	1930
Generator cooling water pump	1,483	45,000	None	None	None	1928
	1,252	45,400	"	"	"	1929
	1,090	34,700	"	"	"	1930

TABLE VI—MAINTENANCE FOR THREE-YEAR PERIOD

Use	Equipment	Maintenance	Man hours
1—D-c. station control	Two—60-cell batteries	Monthly inspection	468
2—Charging batteries	Two—M. G. sets (25 kw.)	Cleaning windings and commutators	90
3—Control power supply from 13.2-kv. system to sta. aux. equipment	Cubicle and other equipment	Cleaning and adjusting contactors, relays, etc.	72
4—Station power and light supply	Three—200 kva., one—100 kva. regulators	Cleaning and inspection of relays, contactors, etc.	66
5—Station auxiliary motor drive equipment	37—220-volt motors driving oil pumps, unit water pumps, etc.	Usual cleaning and inspection	700
6—Automatic control of gov. oil pressure system	Gage type relays and automatic compensator controlling oil pressure	Cleaning and adjusting contacts	850
7—Interlocking pneumatic brakes on generator & main oil circuit breakers	Unit brake valve solenoid	Periodic inspection and cleaning	216
8—Controlling 66-kv. power transformer banks	Transformer bank cubicle recording meters with Selsyn attachment. R.kva., kw., kv. auto. synch. eqpt.	Calibration, changing charts. Detail changes	518
9—To shut unit down in case of trouble on unit	Bearing thermal relays; water-flow indicator; ground relay; overspeed device; phase unbalance relays; loss of gen. field relays; gov. low-oil pressure relay	Monthly inspection, cleaning, adjusting, etc	972
10—Automatic control of generator equipment	Contactors in generator cubicles	Inspection, cleaning, etc., replacing burned-out coils; changing and simplifying control circuit	450
11—Control of generator and transformer cubicles from miniature sup. swbd.	Miniature switchboard 39 rotary control keys	One inspection each control panel; removed from cabinet; contacts and spring tensions adjusted	50
12—Ditto	Miniature switchboard 32 push-button control switches	Periodic inspection, cleaning and testing for proper spring tension	20
13—Ditto	111 miniature indicating lamps (24 volt)	Replacing 50 lamps, inspection and cleaning	27
14—Ditto	Miniature instruments on miniature swbd. indicating kv., kw., r.kva.	Adjustment of bearing friction; replacement of defective spring on one meter and recalibration	45
15—Indicating total kw., r.kva. and kv. on 66-kv. power transf. bank	Selsyn control meters on miniature board	Periodic inspection and cleaning	25
16—Various contactors dependent on polarized relays to energize master circuit to start unit; select proper bus; select method of synchronizing	Polarized relays on cubicles 78 for 8 generators; 2 for 66-kv. transfer bank 3 for sta. aux. bank.	Cleaning, adjusting, etc. Replacing a few coils.	165

TABLE VII—INFORMATION ON SYNCHRONIZING OF GENERATORS

Synchronizing methods	Synchronized		Good shots						
	Successfully	Failure	2 min.	3 min.	4 min.	5 min.	5 to 8	Poor shots	Year
Automatic	1,483	None	890	297	148	74	45	29	1928
Automatic	1,252	None	751	251	125	63	37	25	1929
Automatic	440	None	264	88	40	25	12	11	1930
Self	650	None	Oscillogram shows 2 times normal arm. cur. for 2 cycles. To normal in 15 cycles. System voltage dip = 1.4 volts on 110-volt base						1930

operation of the equipment, resulting in better voltage control, frequency control, and division of load among generating units.

There is a great saving in time during regular operation and human error is largely eliminated.

There is a marked saving in labor costs since there is only one shift operator required to operate the entire station.

Maintenance on the miniature supervisory board is no greater than on vertical boards of older types and, as far as comparisons can be made, appears to be less. Very little trouble has been experienced, apparently slightly less trouble than on older types of boards, although this installation was one of the first used in a large generating station. During system disturbances the operation of the miniature switchboard, as compared with a modern switchboard of standard power house type now in service in Waterside Steam Station (92,000-kw. capacity) indicates that the miniature supervisory board is more convenient, saves time, reduces chances for error, and results in quicker restoration of service.

The use of automatic devices controlling the electrical equipment, waterwheel governor, oil pressure, bearing water pressure, etc., has demonstrated its reliability, low cost of maintenance and inspection, saving of time, saving of operating expense, and better and safer supervision and operation of electrical equipment than would be possible by manual system of control.

This operating experience indicates that hydro plants or steam generating stations can be supervised from miniature switchboards with, or without, automatic features. It is believed that, in hydro plants where units are taken off and put on the bus regularly and frequently, this type of control equipment is not only superior to manually operated equipment but the plant will be operated with greater safety to equipment.

Discussion

M. E. Reagan: The statement regarding increased intervals between maintenance periods corresponds to the experience of a great many operating companies. In fact, one similar equipment has just finished a year's service without breaking the seals on the cases. In other words, there has been no maintenance expense in that time. It is gradually becoming evident that, where the equipment is kept in near-dust-proof cases, the less maintenance the better.

The complaint of the maintenance man is that if he does not experiment with it, he cannot know anything and therefore when trouble does eventually come, he is lost. This is, indeed, false reasoning. He is equipped with complete diagrams, a full set of detailed instructions, and he can see the operations through glass covers or doors. Getting his hands on the relays will not help his situation and may mean disaster to the equipment. His practise on relay adjustment would be much better on spare relays which are not in use.

The type of waterwheel used, while ideal in the application described, has a rather unstable speed characteristic at no-load. In other words, with a small amount of water going through, the machine speed is not uniform and it is hard to synchronize. It has been found in similar installations that a synchronizer with an automatic phase advance feature is desirable. It takes a certain definite time for the circuit breaker to close after the synchronizer makes contact. Within some predetermined lockout speed, the synchronizer automatically makes contact ahead of the "12 o'clock" position in proportion to the speed of the "scope" so that the breaker closes its contacts at synchronism. It also means that the synchronizer will not "pass up" chances for closing the breaker because of the adjustable speed of the wheel.

C. E. Stewart: Considerable advance has been made in the design of suitable control keys and meters for the miniature switchboard during the last few years so that the miniature switchboard is now considered as a standard type of board for installation in power and switching stations. There is no question but what the miniature switchboard meets a very important requirement in the present day designs for handling electrical energy. Undoubtedly the conventional long type of standard switchboard will be eventually superseded by the miniature board because of the improved operating conditions and economies effected.

Economics of High-Voltage Cable

BY D. W. ROPER*
Fellow, A. I. E. E.

Synopsis.—The 132-kv. oil-filled cable placed in service in Chicago in 1927 was designed by the manufacturers in 1925 to have the largest carrying capacity commercially feasible for that voltage in the state of the art as it then existed. During the succeeding years the advancement in the art was so rapid that the cable for the same voltage installed in 1930 had a carrying capacity 75 per cent greater and a cost 20 per cent less than the 1927 line. Improved oil, new designs of oil supply tanks and methods of shipping and connecting cable had reduced the cost of installation and the design of the terminals. Successful operating experience with devices and methods for eliminating sheath losses had removed the previous limitation on the economical size of the conductor. Operating data and test results indicated that the insulation on the first line was thicker than necessary and this led to an inquiry regarding the economy of using the oil-filled type of insulation at higher and lower voltages.

Other questions concerned with future developments in the Chicago region indicated the necessity of a careful study of all recent advances in the art, and resulted in extending the investigations so as to include an economic study of transmission cable for all voltages, present and prospective. The investigations confirmed current practise in the use of three-conductor cable at moderate voltages for transmitting load to substations, but indicated that loads much larger than are ordinary can be efficiently transmitted by the use of single-conductor cable with sheath losses eliminated. A brief statement is included of the method adopted for determining the limitations of oil-filled insulation and extending the present voltage range of oil-filled and ordinary types of insulation.

The recent rate of improvement in the art of high-voltage cable practise probably will be continued in succeeding years.

The utilities must improve their standards of design and workmanship in order to keep pace with improvements being made by the manufacturers.

INTRODUCTION

THE greatest improvement in high-voltage, underground cable in recent years was realized in 1927[1] upon placing in service in New York and Chicago the commercial installations of 132-kv. oil-filled cable. During the installation of these lines it became apparent that a number of improvements was possible, particularly in connection with the methods of installation and oil supply. Methods were devised of making joints on sections of cable filled with oil, and then the shipment of this cable (with a suitable reservoir inside the cable reel for maintaining positive pressure) eliminated the expensive evacuation and impregnation processes in the field that were previously required. A number of these improvements was given a field trial during the installation of oil-filled, three-conductor, 33-kv. cable in Chicago in 1928.[2]

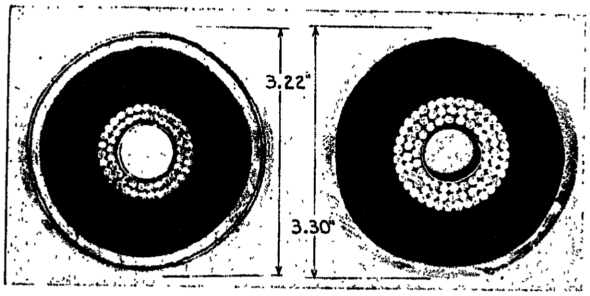

FIG. 1—132-KV. OIL-FILLED CABLES IN COMMERCIAL USE IN CHICAGO

Left: Cable for 103,000-kva. line installed in 1927
Right: Cable for 188,000-kva. line installed in 1930

The fundamental point in the design of an oil-filled line is that positive pressure be maintained on the oil within all portions of the cable under the most adverse conditions, namely, sudden interruption of full load with minimum ambient temperature. In planning the 1930 line for Chicago it was found that there was available an oil electrically similar to the oil used in the 1927 line, but with lower viscosity and lower flow point. This thinner oil permitted a lower oil pressure which made it feasible to use a single lead-tin alloy sheath instead of the double reinforced sheath used in 1927. The reduction in the thickness of the sheath allowed the use of a much larger conductor with slight increase in over-all diameter (Fig. 1), but it was not commercially feasible to increase the conductor size unless the sheath losses were eliminated. Meanwhile, however, favorable operating experience had been accumulating with insulating joints on single-conductor cables in three-phase lines of lower voltage (Fig. 2), and also with the available methods of bonding the cables so as to keep the induced a-c. sheath voltages within

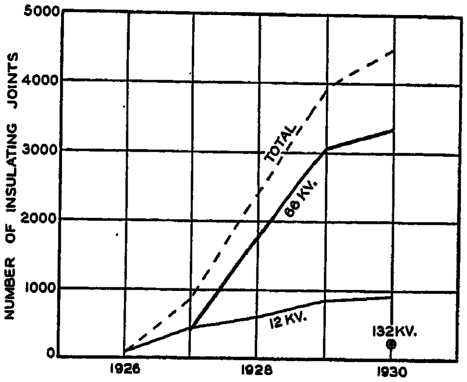

FIG. 2—INSULATING JOINTS IN LEAD SHEATHS INSTALLED ON SINGLE-CONDUCTOR CABLES BY COMMONWEALTH EDISON COMPANY

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*Supt., Street Dept., Commonwealth Edison Company, Chicago, Ill.

[1] For references see Bibliography.

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safe limits.[3] New designs of the oil-supply tanks and the use of the thinner oil simplified the design of the terminals (Fig. 3) for connection to the overhead line.

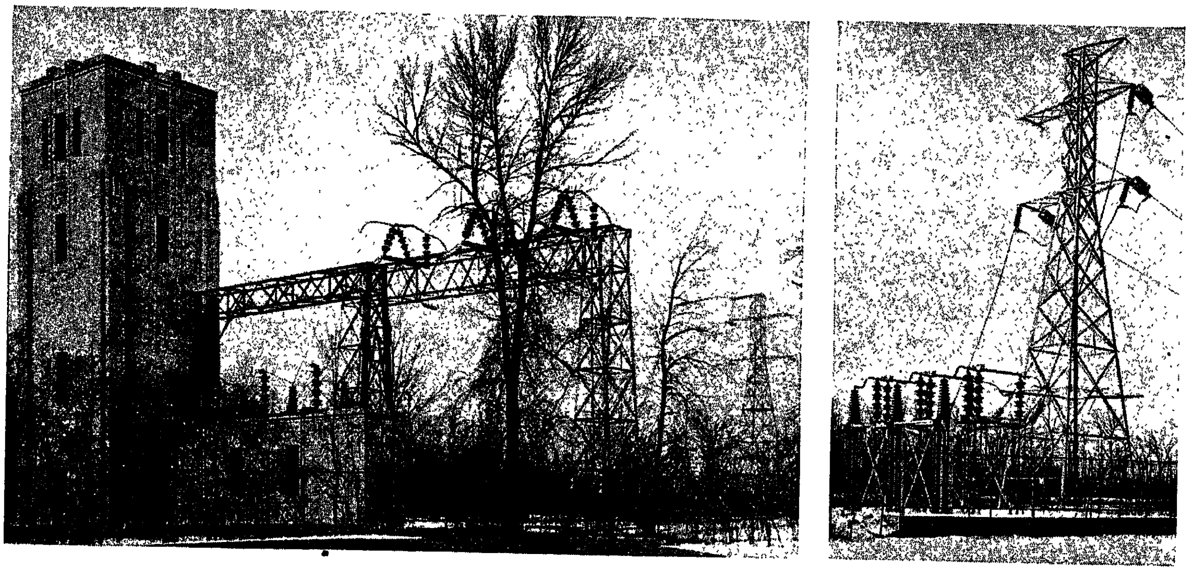


FIG. 3—SIMPLIFICATION IN 132-KV. CABLE TERMINALS DUE TO IMPROVEMENTS IN INSULATING OIL AND RESERVOIRS

Left: Electrically heated terminal and oil reservoir tower of line installed in 1927
Right· Outdoor terminal of line installed in 1930

By taking advantage of all improvements, a line of 188,000-kva. capacity was installed in Chicago in 1930 at a cost about 23 per cent below the cost of the 103,000-kva. line installed in 1927 (Fig. 4). The cost of the 1930 line compares with the 1927 line as follows:

Cable	14 per cent increase.
Joints, oil reservoirs, and accessories	32 per cent decrease.
Supervision and labor for installation	62 per cent decrease.
Special manholes and towers for stop joints and oil reservoirs	81 per cent decrease.
Conduits and ordinary manholes	No change. Same conduit and manholes.
Total	23 per cent decrease.

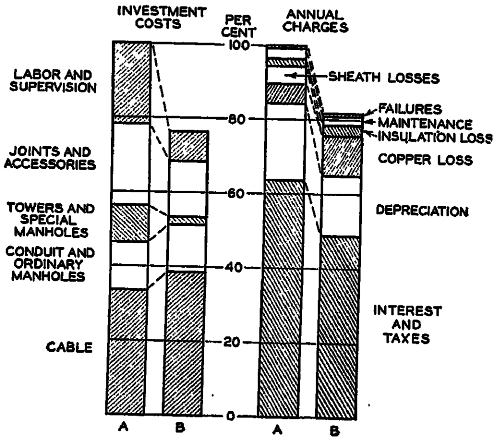
About the same time, other questions arose as follows:

1. What is the maximum economical size of single-conductor cable for connection between the 12-kv. bus and a 60,000-kva. transformer bank?
2. Is there any economy in the use of oil-filled cable for 66-kv. service?
3. What is the maximum load per line that can be carried on 132-kv. oil-filled cable in 4-inch ducts?
4. Can 220-kv. cable be obtained if desired, and what will be the approximate cost?

Therefore it was decided to review for Chicago conditions the entire subject of high-voltage cable so that, in addition to answering all of these questions, it would be possible to determine what changes in existing practise were indicated by recent developments.

PLAN OF PROCEDURE

Preliminary calculations (Fig. 5) on typical cables in use in Chicago indicated wide differences in the relative amounts of the various items entering into the initial cost and annual charges, and, further, that cable with lowest annual charges might not always be the one with the lowest first cost. Accordingly the plan was adopted of calculating curves showing the variations of the initial costs and annual charges for the entire range of commercial sizes so as to secure data which would indicate the most economical transmission voltage and type of cables for various Chicago conditions.



A. 600,000-cir. mil, 103,000-kva. line installed in 1927. Sheath losses present

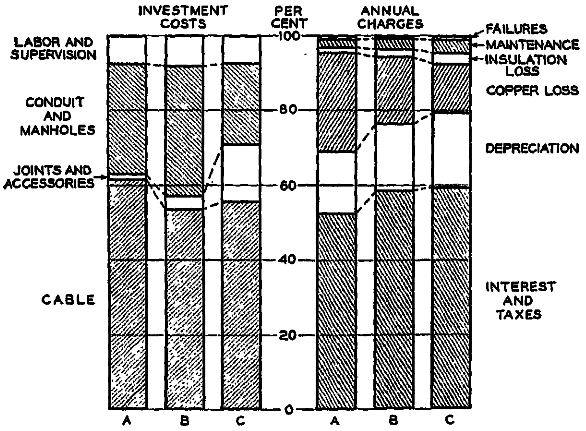
B. 1,100,000-cir. mil, 188,000-kva. line installed in 1930. Sheath losses eliminated

FIG. 4—REDUCTION IN COSTS OF 132-KV. OIL-FILLED LINES IN CHICAGO

There have been no failures in oil-filled cables, but an allowance is made for repairing failures of all kinds including external injuries

The corresponding reductions in investment cost per kva. and annual charges are about 55 per cent

The calculations were confined to cables for the transmission voltages in use in Chicago except that, with some assistance from the manufacturers, 220-kv. cable was added. In determining the size, type or voltage of transmission cable, due consideration should be given to the effect on the entire system of generation, transmission, and distribution of which the cable is to be a part.



A. 12 kv., 3-conductor, 500,000 cir. mil
B. 66 kv., 1-conductor, 750,000 cir. mil
C. 132 kv., 1-conductor, 1,100,000 cir. mil, oil-filled

Fig. 5—Division of Costs for Typical Lines in Chicago

As the relative initial and annual costs were desired under identical conditions, it was considered more important that the unit cost figures be the same for all calculations than that they should fit any particular case. Accordingly for the purpose of these calculations physical constants, unit costs, and conditions were assumed, as given in Table I and in the following assumptions.

Assumptions

1. Impregnated, paper insulated, lead-covered cables installed one per duct.

2. Three-phase, 60-cycle transmission.

3. Engineering details in accordance with Chicago conditions.

4. Three-conductor cables are of shielded type except 12-kv.; conductors are sector-shaped except smaller sizes of 33-kv. and 66-kv. cables.

5. Ducts are round precast concrete, with one-inch concrete between ducts and three-inch envelope.

6. Diameter of cable must not exceed 5/6 of diameter of duct.

7. Pure lead used for ordinary cable sheaths, and 2 per cent tin alloy for oil-filled cable. Sheath thickness for ordinary cables is 5/64 inch for diameters over insulation up to 0.6 inch, and 1/64 inch is added for each increase of 0.6 inch in diameter.

8. Ingot prices of metals per pound: copper, 15 cents; lead, 6 cents; tin, 40 cents.

9. Uniform conductor size used throughout a line. (Actual practise in Chicago is to install larger conductors where cable is in heavily loaded conduits.)

10. No sheath losses on single-conductor cables.

11. Skin effect calculated from data given by Simmons.[4] For three-conductor cables, conductor proximity effect assumed equal to 50 per cent of skin effect and losses due to proximity effect in binding tapes and sheath calculated on basis of formula by Miller.[5]

12. Maximum permissible a-c. sheath voltage to ground is 12 volts.

13. Permittivity of insulation: 3.3 for oil-filled; 3.6 for ordinary.

14. Ambient ground temperature is 15 deg. cent.

15. Annual load factor for 33 kv. and lower voltage cables is 45 per cent as determined by loads found on lines to substations, while for 66 kv. and higher, the load factor is 60 per cent as determined by character of loads on tie lines between stations. Corresponding

TABLE I—TECHNICAL DATA REGARDING THE CABLES ON WHICH CALCULATIONS WERE MADE

Type of cable											
Kv.	No. of conds. per cable	Kind of insul.	Insul. thick. 64ths inch*	Thermal resist. of insul. deg. cent. per watt per cm.^{3}	Max. copper temp. deg. cent.	P. f. of insul. per cent	No. of ducts in conduit	No. of cables in conduit	Average distance between manholes feet†	Duct heating constant deg. cent./watt/ft. of conduit‡	Length of section between stop-joints feet
12	3	A	(11 + 5) – (12 + 6)	700	78	1.8	12	10	400	0.77 – 0.65	
12	1	A	13 – 15	700	83	1.8	12	9	400	0.99 – 0.84	
22	3	A, S	19	600	77	1.6	9	7	400	0.99 – 0.75	
22	1	A	19	600	77	1.6	12	9	400	0.80 – 0.72	
33	3	A, S	25	600	71	1.4	9	7	400	0.80 – 0.68	
33	1	A	25	600	71	1.1	12	9	400	0.80 – 0.68	
33	3	B, S	14 – 18	550	75	0.4	8	6	400	1.10 – 0.82	2,500
66	3	B, S	26 – 28	550	70	0.4	8	6	550	1.10 – 0.82	2,500
66	1	A	48	600	60	0.7	8	6	550	1.00 – 0.82	
66	1	B	26 – 28	550	70	0.4	8	6	550	1.10 – 0.97	2,500
132	1	B	46	550	70	0.4	8	6	550	1.10 – 0.82	2,500
220	1	B	72	550	65	0.4	8	6	550	0.97 – 0.82	2,500

A—Ordinary type of insulation. B—Oil-filled insulation. S—Shielded type of 3-conductor cable.

*Increased thicknesses are for large conductors.

†For very large single-conductor cables, these lengths would have to be reduced by as much as 30 per cent in order to keep the induced sheath voltage to earth from exceeding 12 volts.

‡Smaller heating constants are for the larger cables requiring larger duct sizes.

daily load factors for winter week day are 55 per cent and 75 per cent.

16. Joints for 33 kv. and above are oil-filled.

17. Oil-filled lines are equipped with signal systems to indicate oil leaks.

18. No credit is given in principal calculations for charging kva. of cables and no allowance for neutralizing charging current of very long high-voltage lines.

19. Transmission line voltage drop not considered.

20. Fixed charges on investment: conduit, 10½ per cent; cable, 11½ per cent; terminals, 12½ per cent.

21. Cost of energy losses, 0.6 cents per kw-hr.

22. Rate of cable failures, 1½ to 3 per 100 mile-years; rate of joint failures, ⅛ to 1⅛ per 1,000 joints per year. Higher rates apply to lower voltages.

Methods and Results of Calculations

Using the carrying capacities of the cables as shown in Fig. 6, corresponding curves were calculated showing the cost of the conduit and manholes (Fig. 7), the cost of the cable installed in conduit (Fig. 8), the cost of the joints and accessories (Fig. 9), and the cost of terminals (Fig. 10). From these data were calculated the initial cost (Fig. 11) and annual charges (Fig. 12) of the completed lines without terminals, also corresponding curves of 10-mile lines with terminals (Figs. 13 and 14).

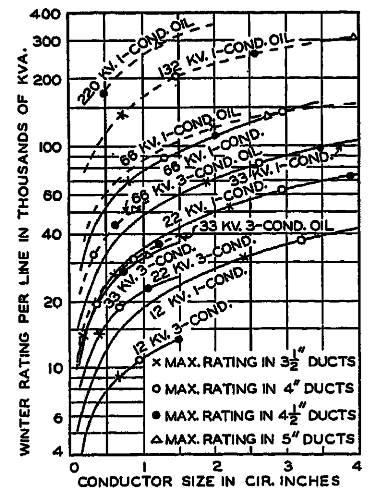


Fig. 6—Carrying Capacities of Lines

No sheath losses on single-conductor cables. Cable diameter not more then five-sixths of duct diameter. Cables are of ordinary type unless otherwise specified.

As single-conductor cables require three ducts per line, the cost curves per kva. for conduit and manholes for these cables (Fig. 7) appear in a separate group considerably higher than the corresponding curves for three-conductor cable.

For the 66-kv., single-conductor cable, it is interesting to note (Fig. 8) that the oil-filled cable costs less than the ordinary type due to less copper, insulation, and lead. The relative cost figures are reversed for the 33-kv., three-conductor cable.

The curves showing the costs of the joints and accessories arrange themselves in three groups, the first containing the three-conductor cables with the ordinary type of insulation; the second group containing single-conductor cable with the ordinary type of insulation having three times the number of joints as for three-conductor cables and, in addition, the cost of the insulating joints and devices for eliminating the lead sheath losses; the higher cost figures for the third group, which includes the oil-filled cables, is due largely to the cost of the stop joints, oil reservoirs and accessories required with this type of cable.

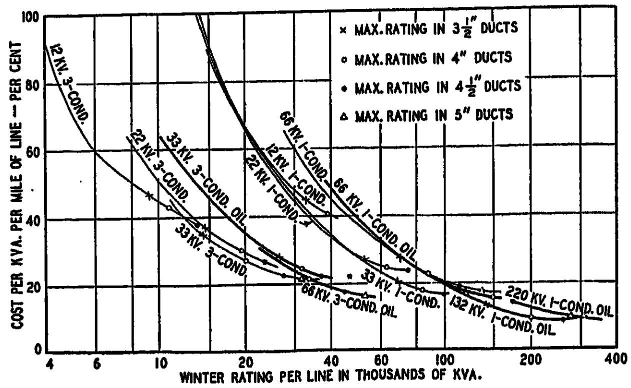


Fig. 7—Relative Costs of Conduit and Manholes per Line

One cable per duct. Vertical scale same as Fig. 8

A study of the curves leads to the following conclusions:

1. The most economical cable for a given set of conditions should be determined by considering the total annual charges, rather than the first cost.

2. The inclusion of the terminal charges makes but slight difference in the *relative* costs of the various types and voltages of cable. This indicates that the relative costs of the various types and voltages of cable would be only slightly altered by assumptions somewhat different from those used in the calculations.

3. For every load there is one type of cable and one transmission voltage which is more economical than any other combination. (See Table II.)

4. For a given type and voltage of cable, maximum economy is generally found with larger cables than are in ordinary use.

TABLE II—MOST ECONOMICAL TYPES OF CABLE FOR VARIOUS RANGES OF LOAD

Data Taken from Fig. 12

	Most economical type of cable		
Load range—kva.	Voltage—kv.	No. of conductors	Kind of insulation
Up to 8,000	12	3	Ordinary
8,000— 12,000	22	3	Ordinary
12,000— 25,000	33	3	Ordinary
25,000— 48,000	66	3	Oil-filled
48,000—120,000	66	1	Ordinary
120,000—260,000	132	1	Oil-filled

5. Three-conductor cables are the most economical for loads up to about 50,000 kva. For the upper half of this range, three-conductor, 66-kv., oil-filled cable[6] is the most attractive, but it requires larger ducts than are now in ordinary use.

6. For loads above 50,000 kva. per line, single-conductor cable should be used.

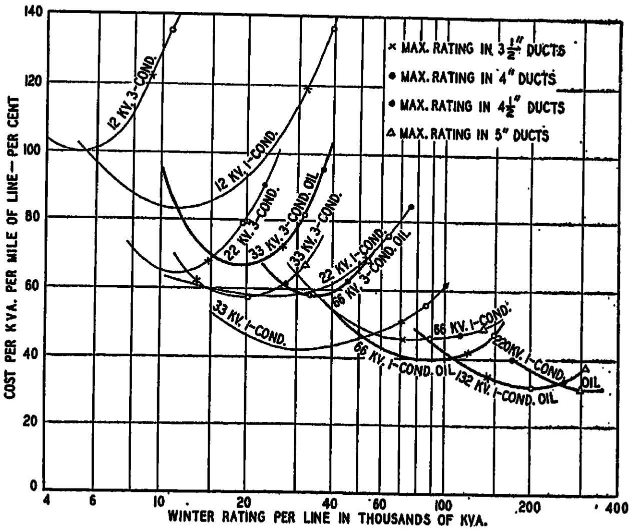


Fig. 8—Relative Costs of Cable Installed in Conduit

Costs include racks and fireproofing but do not include joints, oil reservoirs, and other accessories. Minimum cost for 12-kv., 3-conductor cable assumed as 100 per cent.

7. The elimination of sheath losses permits the efficient use of large single-conductor cables between 12-kv. bus and transformers for high-voltage lines.

8. For cable to operate at 66 kv., a moderate reduction in the cost of oil-filled, single-conductor cable and in the cost of the joints and accessories would bring the oil-filled type in competition on a cost basis with cable of the ordinary type.

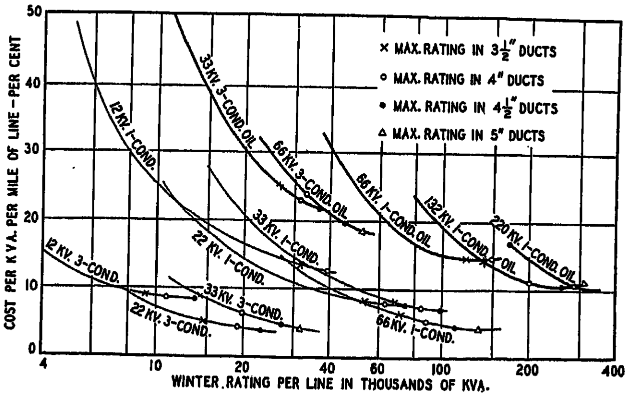


Fig. 9—Relative Cost of Joints and Accessories Installed

Includes oil reservoirs and apparatus for eliminating sheath losses. Vertical scale same as Fig. 8

9. For loads of the order of 100,000 kva. per line, oil-filled, 66-kv., single-conductor cable is preferable to the ordinary type when the over-all diameter of cable is limited by the size of the ducts in existing conduits.

10. There is no economy in using 132 kv. for tie lines between stations in Chicago until the required carrying capacity exceeds 125,000 kva. per line. In so far as carrying capacity of the cable is concerned, there is no occasion for increasing the transmission voltage above 132 kv. until the required capacity per line exceeds 250,000 kva.

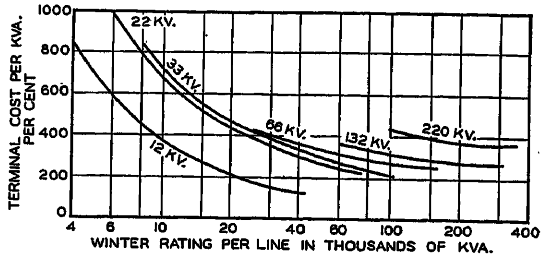


Fig. 10—Relative Terminal Costs

Terminal costs include only a simple connection between cable and bus without high-voltage bus ties or other auxiliary switches as follows:

(a) 12-kv. oil-circuit breaker and portion of switchhouse at generating station

(b) Oil circuit breaker at substation end of 12-, 22-, and 33-kv. lines

(c) Transformers and high-voltage bus structure at generating station for all lines above 12 kv.

(d) Terminal structure and disconnective switches at other end of 66-, 132-, and 220-kv. lines

Vertical scale same as Fig. 8

11. The cost of cable for 132 kv. and higher voltages probably will limit its use to underground extensions, within large cities, of long, overhead transmission lines from distant stations.

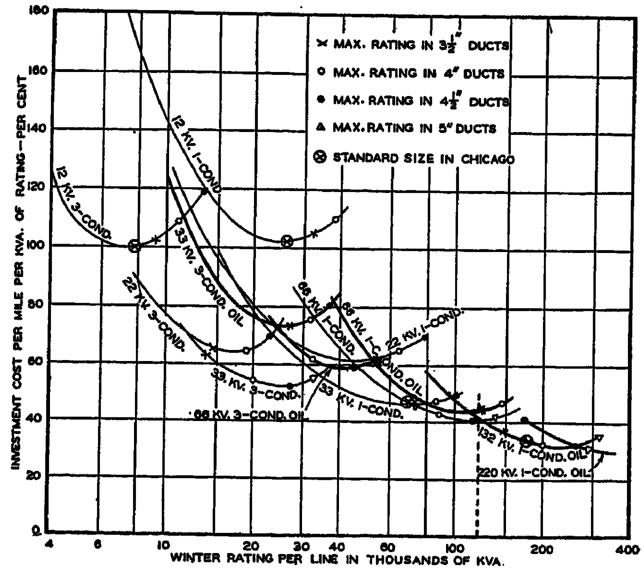


Fig. 11—Relative Investment Costs of Underground Lines, Excluding Terminals

One cable per duct: 6 to 10 identical cables per conduit. Minimum cost for 12-kv., 3-conductor cable assumed as 100 per cent.

12. As the fixed charges are about three-fourths of the total annual charges, the best way to reduce annual charges is to reduce first cost.

13. In determining the best transmission cable for a given purpose, the decision should not be restricted by preconceived ideas of the relative importance of transmission voltage, dielectric loss, skin effect, maximum efficiency of insulation, Kelvin's law, the size or number of ducts in the conduit, or other physical laws and constants; but, by taking all such subjects into consideration, the type, size and voltage of cable and conduit details should be determined so as to secure the lowest annual charges for the given conditions.

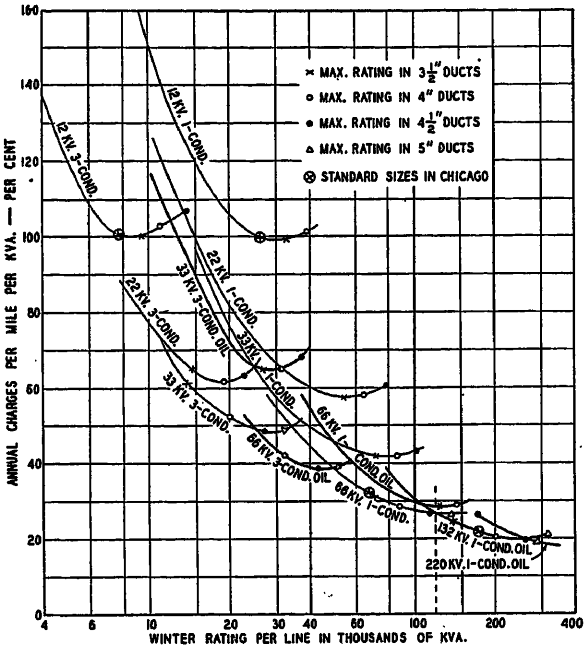


Fig. 12—Relative Annual Charges for Underground Lines, Excluding Terminals

Annual load factors: 12 kv. to 33 kv., 45 per cent, 66 kv. to 220 kv., 60 per cent. Minimum charges for 12 kv., 3-conductor cable assumed as 100 per cent.

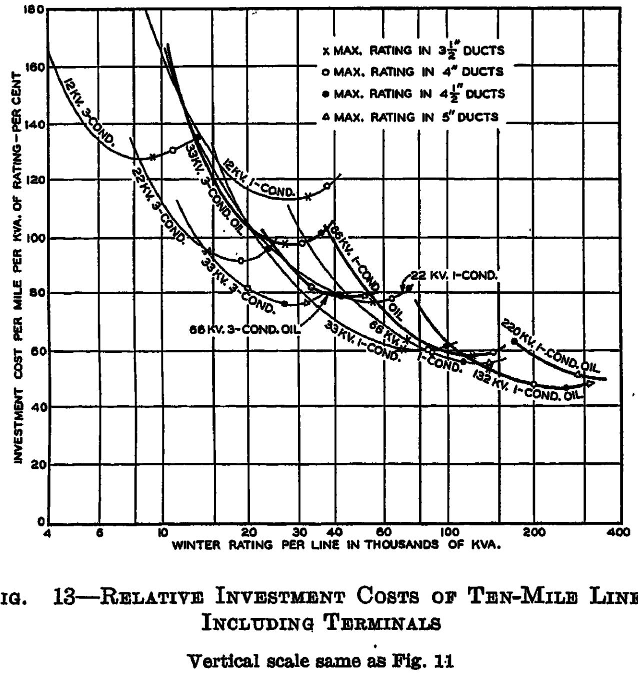


Fig. 13—Relative Investment Costs of Ten-Mile Lines, Including Terminals

Vertical scale same as Fig. 11

Discussion of Factors Affecting Cost

The elimination of sheath losses on single-conductor cables permits a considerable increase in the rating of the cables and a corresponding reduction in the annual charges. (Figs. 15 and 16.) The devices used for the elimination of the sheath losses on the 132-kv. oil-filled line installed in 1930 are shown in Fig. 17.

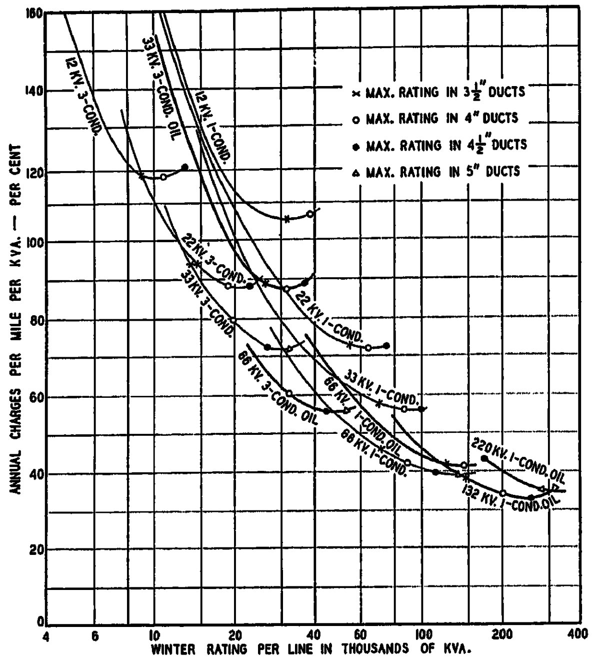


Fig. 14—Relative Annual Charges for Ten-Mile Lines, Including Terminals

Annual load factors: 12 kv. to 33 kv., 45 per cent, 66 kv. to 220 kv., 60 per cent. Cost of transformer losses included. Vertical scale same as Fig. 12

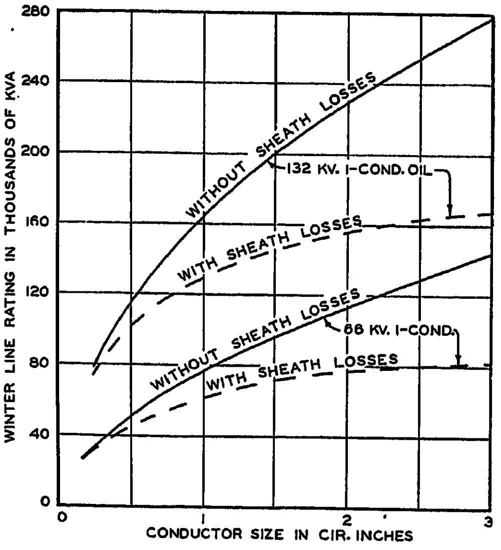


Fig. 15—Effect of Sheath Losses on Carrying Capacities of Cables

In calculating the carrying capacities, the dielectric loss was assumed in accordance with recent test data, as shown in Fig. 18, in which there is also shown the effect on the carrying capacity and on the annual charges of different power factors from those assumed. These graphs show the necessity of continually decreasing the power factor with increase in operating voltage.

The maximum permissible operating temperatures of cables of all voltages are shown in Fig. 19. The effect on the annual charges of changing the maximum copper temperature for typical cables is shown in Fig. 20.

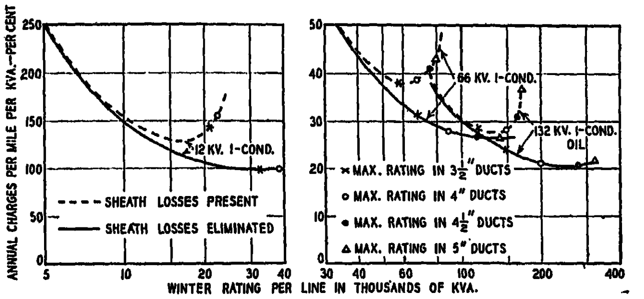


Fig. 16—Effect of Sheath Losses on Annual Charges for Single-Conductor Cables

Annual load factors: 12 kv. to 33 kv., 45 per cent, 66 kv. to 220 kv., 60 per cent. Vertical scale same as Fig. 12

It will be noted that the advantage of increased maximum operating temperature is greater for the high-voltage cables, and, further, there is but slight advantage in increasing the temperature for any type beyond 85 deg. cent. A temperature survey of the lines in Chicago shows that but a small portion is operating near the maximum permissible temperature (Fig. 21).

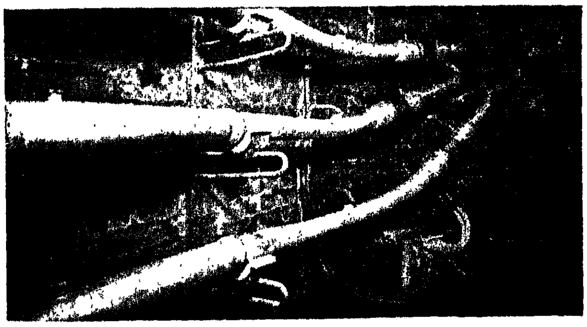


Fig. 17—Installation of Equipment for Eliminating Sheath Losses on 132-Kv., 188,000-Kva. Underground Line Installed in Chicago in 1930

Left: Normal cable joints before fireproofing
Center Right: Insulating joints in cable sheaths
Lower Right: Bonding transformer for reducing sheath voltages

The rating of cables installed in conduit is determined by the total amount of heat to be radiated from the conduit. Increasing the number of cables per conduit beyond rather moderate figures does not reduce the annual charges, as shown in Figs. 22 and 23.

While an increase of load factor increases the amount of energy to be radiated from the conduit and thus reduces the rating of the cables, this reduction is more than offset by the increased energy transmitted as shown in Fig. 24.

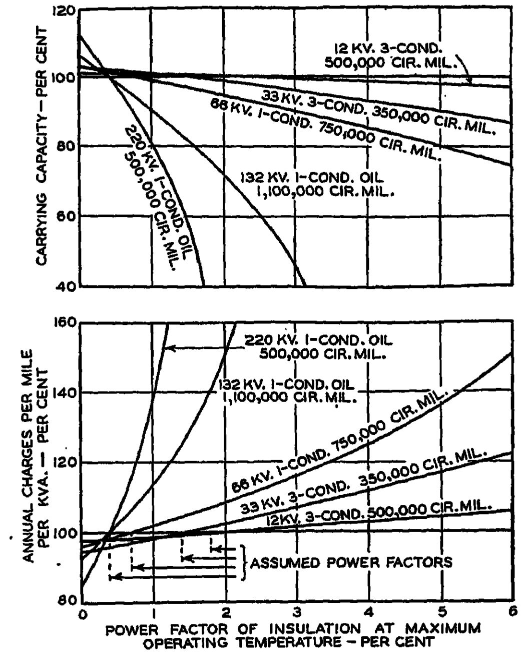


Fig. 18—Effect of Changes in Insulation Losses in Carrying Capacities and Annual Charges for Typical Cables

Assumed power factors are in accordance with recent test data as follows:
12 kv., 3-conductor, 1.8 per cent @ 78 deg. cent.
33 kv., 3-conductor, 1.4 per cent @ 71 deg. cent.
66 kv., 1-conductor, 0.7 per cent @ 60 deg. cent.
132 kv., 1-conductor, oil-filled, 0.4 per cent @ 70 deg. cent.
220 kv., 1-conductor, oil-filled, 0.4 per cent @ 70 deg. cent.

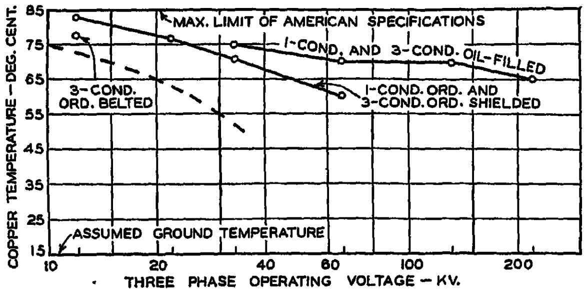


Fig. 19—Maximum Copper Temperatures Assumed in Calculations. Dashed Line shows Limits Set by A. I. E. E. Standards as of 1922. At that Time, the Highest Voltage Cable was 33 Kv., 3-Conductor, Belted

For cables below 66 kv., the charging current is not a large item; but for 66 kv. and higher voltage cables, the charging current is sufficient to affect appreciably the power factor of the system to which they are connected. If the improvement in power factor obtained in this manner is important, then some credit should be given to the cost of the cables on this account. If the credit is figured on the same basis as the cost of obtaining the same improvement in power factor with synchronous condensers, the reductions in the annual charges for high-voltage cables would range from 8 per cent for 66-kv., single-conductor cable with the ordinary type of insulation, to 34 per cent for 220-kv. oil-filled insulation, as shown in some further detail in Fig. 25.

COMPARISON OF THE ORDINARY AND THE OIL-FILLED TYPES OF CABLE

As the competition between these two types is closest at 66 kv., their status may best be shown by an examination of the detailed costs of the two types of 66-kv., single-conductor cable for 65,000-kva. carrying capacity as given in Fig. 26. The comparative sizes of the two cables are indicated by Fig. 27. About 260 miles of such cable with the ordinary type of insulation are now in service in Chicago.

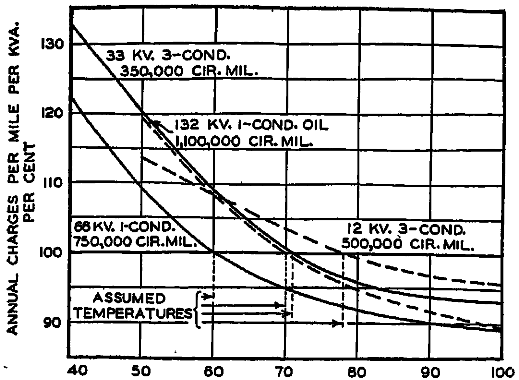


FIG. 20—EFFECT OF ANNUAL CHARGES OF CHANGES IN MAXIMUM COPPER TEMPERATURES

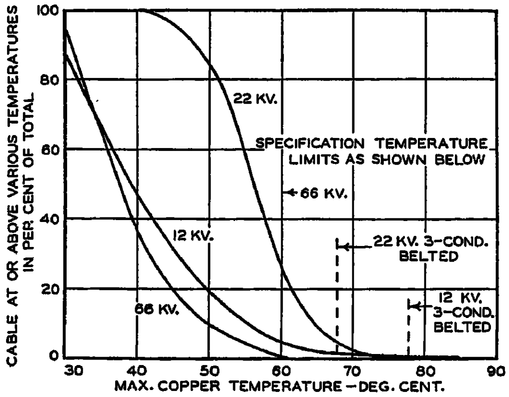


FIG. 21—OPERATING COPPER TEMPERATURES OF TRANSMISSION CABLES IN CHICAGO

Results of survey at time of maximum temperature, which in Chicago occurs in summer-time

In these comparisons it should be noted that the conditions in Chicago are favorable to the oil-filled type of cable. The maximum difference in elevation of portions of the city in which high-tension cables are now installed, as determined from U. S. Geological Survey maps, is less than 30 feet, thus reducing the number of expensive stop joints and oil-reservoir manholes to a minimum.

For 66-kv. lines of 120,000 kva. capacity, contemplated for the future in Chicago, there is an advantage in the oil-filled type as its smaller diameter permits it to be installed in vacant 4-inch ducts of existing conduits along different routes, while the use of the ordinary type would require the construction of special conduits with larger ducts and make it more expensive to secure different routes for the several lines.

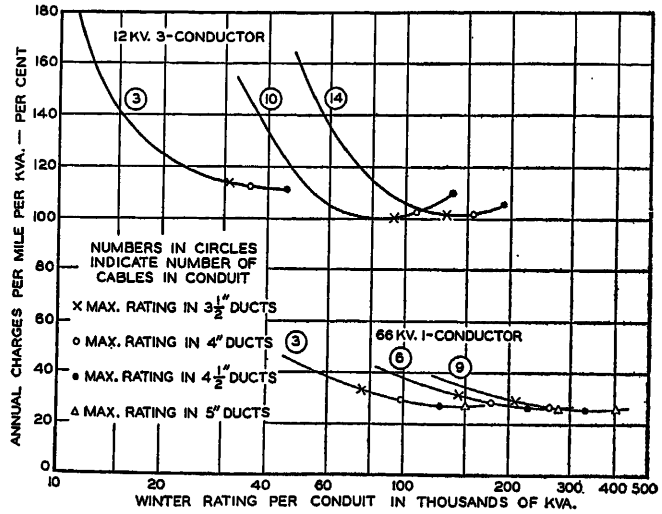


FIG. 22—EFFECT ON ANNUAL CHARGES OF NUMBER OF CABLES IN CONDUIT.

Vertical scale same as Fig. 12

For 65,000-kva. capacity at 66 kv., the cost of the joints and accessories of the oil-filled type is nearly four times that of the ordinary type. If the cost of the joints and accessories for the oil-filled type could be reduced by 50 per cent, it would be more than offset by a reduction of 15 per cent in the cost of the ordinary type of cable which might be realized by a reduction in the thickness of insulation. With free competition

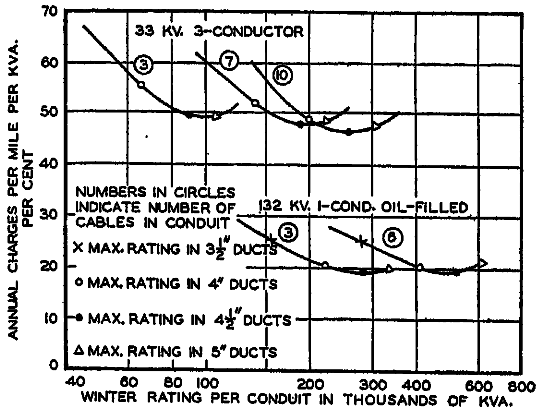


FIG. 23—EFFECT ON ANNUAL CHARGES OF NUMBER OF CABLES IN CONDUIT.

Vertical scale same as Fig. 12

such a reduction does not seem impossible in view of the fact that one make of such cable in Chicago with 0.75-inch insulation had no failures of insulation in a service record of 266 mile-years of operation up to March 1, 1931. It also appears that some reductions in the cost of the oil-filled cable might reasonably be expected as the oil-filled type, shown in Fig. 27, uses 19 per cent less copper, 55 per cent less paper, and 32 per cent less lead than the ordinary type, with a consequent reduction of 34 per cent in the weight.

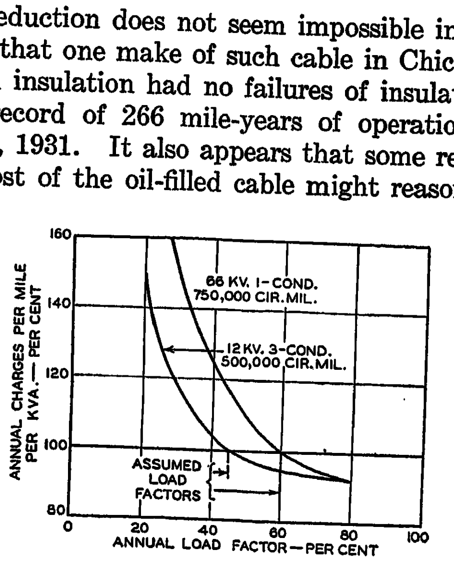


FIG. 24—EFFECT ON ANNUAL CHARGES OF CHANGES IN LOAD FACTORS

Interesting information in this connection has been obtained from an experimental installation in 1927 at 108th Street (Figs. 28 and 29) of several 1,000-ft. lengths of cable with the ordinary type of insulation and one length of oil-filled cable as installed on the commercial line in 1927 (Fig. 1). These cables were operated at first with applied voltage only and without load; later daily load cycles were added and increased at intervals so as to raise the maximum temperature of the cables. In Fig. 30 are shown power-factor measurements of one typical sample of ordinary type of insulation operated to a maximum temperature of 60 deg. cent. and also the similar readings for the oil-filled cable operated to a maximum temperature of 75 deg. cent. From these curves it will be noted that there was a continuous change in the ordinary type of insulation, indicating instability at this voltage, while in the oil-filled type there was practically no change after 19 months' operation. This indication of stability of the oil-filled insulation, together with the perfect operating record of the oil-filled cable in New York and in Chicago indicated that probably 0.72-inch oil-filled insulation was more than required for 132-kv. operation. Accordingly additional samples of oil-filled cable having approximately 0.50-inch and 0.40-inch insulation have been installed at 108th Street and operated with gradually increasing loads, as above described, with the object of determining the maximum operating

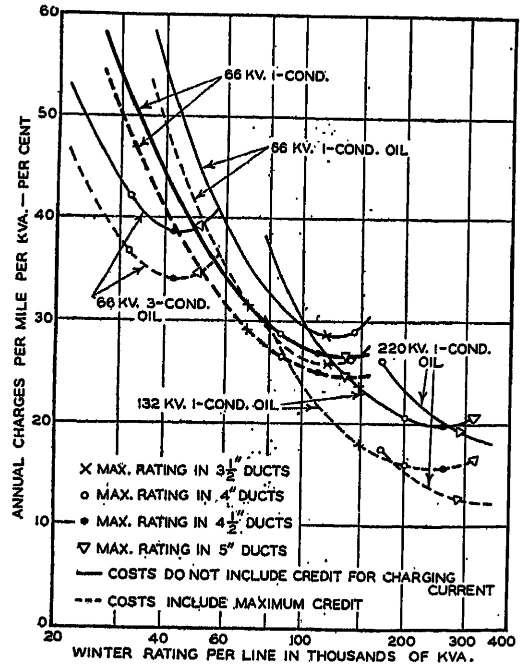
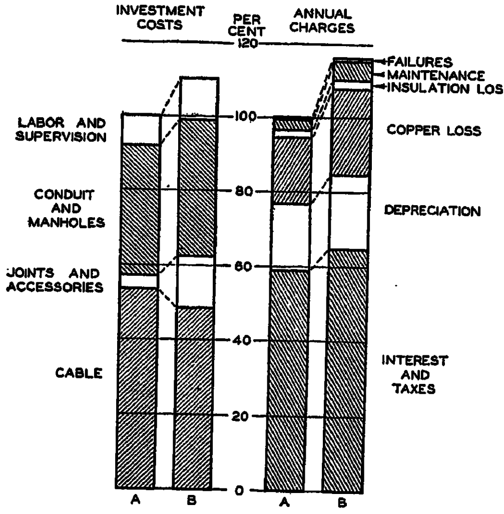


FIG. 25—REDUCTION OF ANNUAL CHARGES FOR HIGHER VOLTAGE CABLES WITHOUT TERMINALS BY ALLOWING MAXIMUM CREDIT FOR CHARGING CURRENT

Vertical scale same as Fig. 12



A. Ordinary *B.* Oil filled

FIG. 26—COMPARISON OF COSTS OF SINGLE-CONDUCTOR ORDINARY AND OIL-FILLED 66-KV. LINES HAVING SAME CARRYING CAPACITY (65,000 KVA.) SHOWN IN FIG. 27

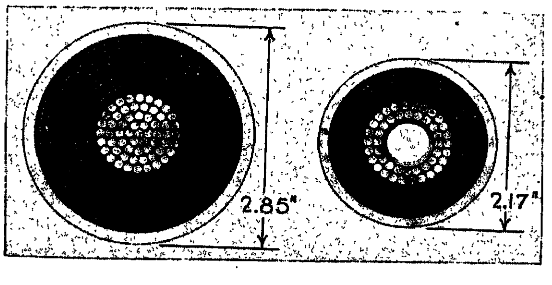


FIG. 27—66-KV. CABLES OF SAME CARRYING CAPACITY

(Left) 750,000-cir. mil, 0.75-in. ordinary insulation. Maximum temperature 60 deg. cent.

(Right) 580,000-cir. mil, 0.406-in. oil-filled insulation. Maximum temperature 70 deg. cent.

stresses and maximum operating temperatures for oil-filled insulation.

A comparison of typical power-factor curves of cables with normal and reduced oil-filled insulation (Fig. 31) indicates that after daily load cycles for nearly eight months, oil-filled insulation 0.50-inch thick is about as stable at 132 kv. as the 0.72-inch insulation.

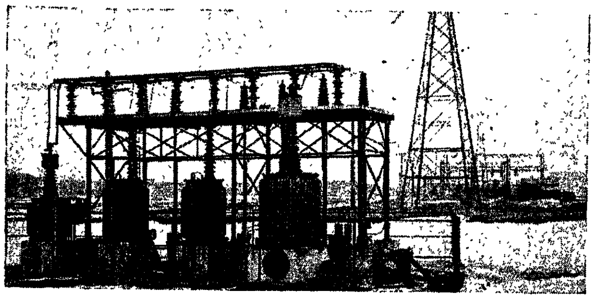


Fig. 28—108th Street Field Laboratory for 1,000-Ft. Lengths of 132-Kv. Cables

Foreground: Circulating current transformers for heating cables
Center: Towers of 132-kv. line to which cables are connected
Right Rear: Laboratory for dielectric loss measurements

These curves also show a curious improvement in power factor which is somewhat more obvious by a direct comparison of ionization factors, as shown in Fig. 32. The diameter of a 132-kv. cable would be reduced almost 20 per cent (Fig. 33) with improvements that do not appear remote.

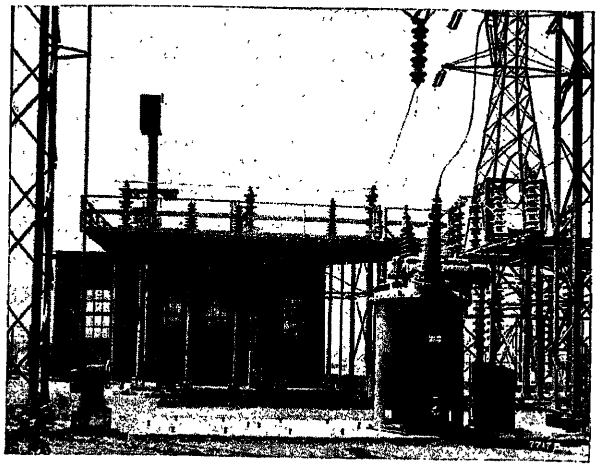


Fig. 29—Laboratory for Testing 132-Kv. Experimental Cables and Arrangements for Connecting Cables to Overhead Line

In considering the feasibility of securing cable of the ordinary type for operation at 132 kv., the most optimistic assumption is that the operating voltage can be increased in proportion to the increase in thickness of the insulation. The maximum thickness of impregnated paper insulation which has been suggested by cable manufacturers is 1.125 inches. The operation of this thickness of ordinary insulation at 132 kv. would then correspond to a thickness of insulation of 0.563 inch for 66 kv. This insulation would operate at approximately the same average stress as the 60-kv., three-conductor cables now in operation in Paris with 13 mm. (0.51-inch) insulation. When successful operating records of 66-kv. cable with 0.55-inch insulation are available, or when 132-kv. experimental cable with less than 1 inch of insulation will withstand tests such as shown in Fig. 29 without signs of instability, then

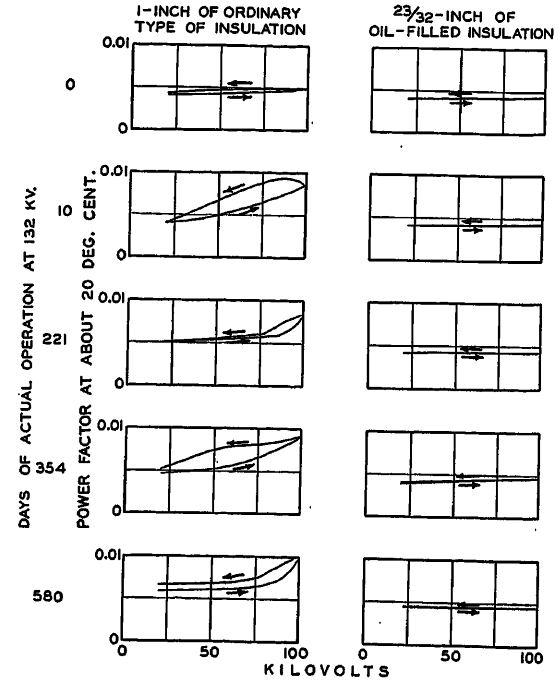


Fig. 30—Typical Power-Factor Voltage Curves for 132-Kv. Experimental Cables in Chicago

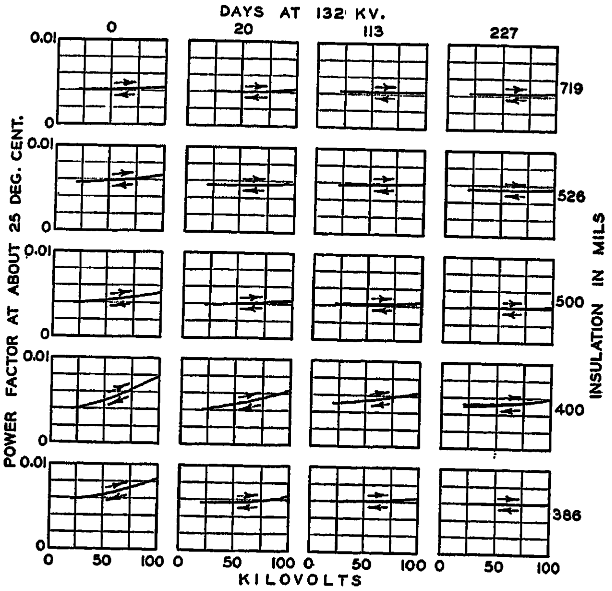


Fig. 31—Typical Power-Factor Voltage Curves for Two Makes of 132-Kv. Experimental Oil-Filled Cable In Chicago

Cable is subjected to daily load cycles with maximum copper temperature of about 70 deg. cent.

it will be in order to consider the commercial use of the ordinary type of insulation at 132 kv. Calculations indicate that on this basis the ordinary type would compete economically with the oil-filled type at 132 kv.

The use of 1.125-inch oil-filled insulation at 220 kv. would be equivalent to 0.675 inch at 132 kv. on an average stress basis. Taking into consideration all available information, it appears that there would be less risk at present in operating oil-filled cable at 220 kv. than in operating the ordinary type at 132 kv.

Whether the oil-filled type will displace the ordinary type at 66 kv. and lower voltages or the ordinary type compete with the oil-filled type at 132 kv. depends on the relative rates of improvement in the two types of insulation with unrestricted competition.

In comparing the two types of insulation and in considering reductions in thickness of the oil-filled type of insulation, very careful consideration must be given to the effect of transient voltages due to switching or lightning. The best available information is that the short-time breakdown strength of a given thickness of the ordinary type of insulation is about as high as for the oil-filled type. More information on this subject is very much needed; in the meantime when considering reductions in thickness of oil-filled insulation for cables connected to an overhead line, all possible precautions should be taken for limiting the transient voltages to which the insulation may be subjected.

These investigations with the reduced thickness of oil-filled insulation were preliminary to the design of 220-kv. oil-filled cable. An experimental installation of 220-kv. cable had been planned for the Crawford Avenue Station upon the completion of an overhead 220-kv. line into that station in the fall of 1932. In view of the advances in the art of testing cable as indicated in this and other papers presented at the same meeting, it now appears that the expense of this experimental installation of 220-kv. cable, similar to the installation of 132-kv. cable at 108th Street, is not warranted as all required information can be obtained by means of laboratory facilities now available.

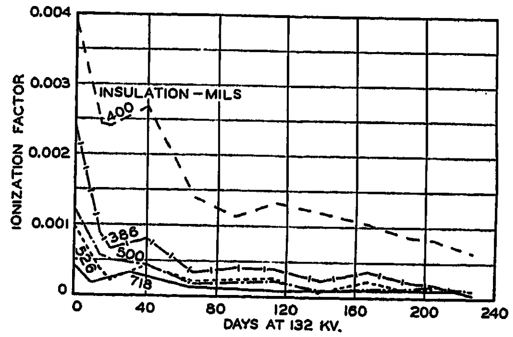


FIG. 32—VARIATION OF IONIZATION FACTOR (INCREASE IN POWER FACTORS FROM 20 TO 100 KV.) WITH AGE FOR TWO MAKES OF EXPERIMENTAL 132-KV. CABLE IN CHICAGO

Tests at about 25 deg. cent.

LEAD SHEATHS

In considering future developments in high-tension cable the lead sheath should not be overlooked. In recent years the number of failures and replacements of high-voltage cable due to defective lead sheaths have been about equal to the number due to defective insulation. One foreign manufacturer claims to have eliminated cable sheath failures by the use of a lead press of a design differing from any in use in this country.[7]

Lead sheath appears to have an "elastic limit" at about 175 lb. per square inch, that is, there is no stretching at such tensions when long continued. These pressures correspond to about 18 lb. internal pressure on a lead sheath 3 inches in inside diameter. It would reduce the cost of the accessories for the oil-filled type and permit increasing the maximum temperature of the ordinary type if an alloy could be discovered which would raise this elastic limit.

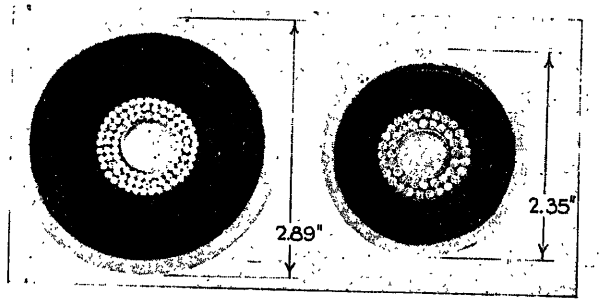


FIG. 33—REDUCTION IN SIZE OF 132-KV. CABLE, IF THE INSULATION THICKNESS WERE REDUCED FROM 0.72 TO 0.50 IN. AND THE MAXIMUM TEMPERATURE INCREASED FROM 65 TO 80 DEG. CENT.

(Left) 600,000-cir. mil commercial cable
(Right) 475,000-cir. mil experimental cable

LOOKING FORWARD

When all the research investigations now in progress or contemplated by the utilities, universities, and manufacturers have been brought to a successful conclusion:

1. Cables of all types and voltages will be operated at a maximum temperature of 85 to 90 deg. cent. without fear of deterioration.
2. The expensive oil reservoirs and accessories on oil-filled cable will be eliminated due to:
    a. Increase in the elastic limit of the cable sheath.
    b. Reduction in the thermal coefficient of expansion of the oil.
    c. Making the insulation somewhat compressible under moderate pressures existing with the lead sheath.
3. An installation of oil-filled cable will be no more complicated than a present-day installation of ordinary type of cable.

4. Cable of subnormal quality will be eliminated by tests at the factory.
5. The initial cost per kva. of 66-kv. cable completely installed will be from 30 to 40 per cent below the present cost of the ordinary type.
6. Cable failures due to all causes will not exceed one per hundred miles per year.

If all of these results should be achieved within the next 15 years, it would be no more startling than a statement of the present day state of the art would have appeared 15 years ago.

In order that the utilities may realize the benefits of such improvements in quality of cable, their standards of design and construction of conduits and manholes, workmanship during installation and splicing, as well as the standards of operation, inspection and maintenance, must be increased in at least the same ratio as the improvement in insulation.

ACKNOWLEDGMENT

The author gratefully acknowledges his indebtedness to those of his own staff and of the Engineering Department who have contributed so generously to the preparation of this paper. In particular he is indebted to Herman Halperin who had general supervision of the assembly of the data and preparation of curves, and in addition contributed many helpful suggestions.

Acknowledgment is also made to F. O. Wollaston who, assisted by D. D. Nagley, made the calculations for the numerous curves; to G. M. Armbrust and J. B. Jackson of the Engineering Department for information regarding terminals and conduits; and to G. B. Shanklin of General Electric Company and D. M. Simmons of General Cable Corporation for assistance in connection with 220-kv. cable.

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Discussion

For discussion of this paper see page 1447.

Characteristics of Oil-Filled Cable

BY G. B. SHANKLIN*
Member, A. I. E. E.

and

F. H. BULLER*
Member, A. I. E. E.

Synopsis.—*This paper deals briefly with the general theory and some of the outstanding characteristics of oil-filled cable practise. Oil-filled cable has had a perfect operating record during the past four years and during this time many simplifications and economies have been introduced. Further gains in this direction are indicated. Today, this type of cable is well in line with ordinary paper-insulated cable from an economic standpoint.*

The limiting features of oil demand and oil supply are explained and typical methods of oil feed with expansible reservoirs described. Space does not allow the inclusion of many additional things of interest such as a description and drawings of the complete line of cable and accessories that have been developed.

* * * * *

INTRODUCTION

RAPID progress is being made in oil-filled cable practise. The space limitations of this paper make it impossible to deal with the many phases of this activity, and the subject matter will be confined to a brief summary of the more important electrical and physical characteristics. The oil-filled cable is now past its infancy. The theory and principles are well understood and the technical soundness of these is fully substantiated. Much of this work has been described in the technical press. If the reader will refer to publications (1) to (9), inclusive, in the Bibliography, and include the contents of the present paper, he will have a fairly complete story of oil-filled cable practise as it exists today.

Large installations of 132-kv. cable, and others of lower voltage rating, have been placed in service during the past four years. All of these have operated with outstanding success, and each successive installation has represented an improvement in the way of simplification and economy. There is good reason for assuming that further gains will be made. Even today, high-voltage, oil-filled cable is well in line with ordinary "solid" cable from an economic standpoint.

The economic dividing line is not sharply defined because of the large number of factors involved. Such factors as voltage rating, load per circuit, single conductor or three conductor, size of ducts available, etc., determine whether oil-filled or solid cable is the more economical. At present there is a rather wide overlap. As further progress is made this overlap will be lowered and narrowed. Even if this expectation is not completely fulfilled, there still remains an overlap from 30,000 to 70,000 volts, grading off at each end, where choice is a matter of local conditions and requirements. Above 70,000 volts rating, oil-filled cable is already in the lead from every standpoint.

ADVANTAGES

Some of the advantages of oil-filled cable, as compared with solid cable are:

a. Voids are entirely eliminated, if the installation is properly designed, and insulation deterioration is not a factor to contend with.

b. Maximum safe operating temperature is higher and fluctuations in load and seasonal temperature are not important.

c. The thickness of insulation is about half that for solid cable, resulting in a smaller, lighter cable, or for equal over-all diameters, a cable of larger conductor size and greater current carrying capacity.

d. For a given size duct, much more power can be carried by oil-filled cable, for the reasons outlined.

e. The maximum safe voltage rating for single-conductor, solid cable is about 75 kv.; oil-filled cable has extended this to 132 kv., and 220 kv. appears possible when required.

f. The maximum safe voltage rating for three-conductor, solid cable is about 45 kv., because of physical limitations; oil-filled cable has extended this to 75 kv. and even higher voltage is possible.

g. Positive oil pressure is maintained and because of this, flaws and defects in the lead sheath merely result in slow leakage of oil, which can be located and repaired at any convenient time. Electrical service failure, caused by entrance of moisture and air, is usually the first warning of such defects in solid cable.

COMPLICATIONS

Some of the supposed complications and disadvantages of oil-filled cable have never actually existed. Others were the result of pioneer procedure, where simplicity and economy were either not fully developed or were sacrificed in the interests of surety, until the experimental stage could be passed. Alert engineering and knowledge of a few new principles are necessary. It is in this direction that most of the complications lie, but many engineers now recognize that this new knowledge could also be profitably employed in solid cable practise.

The fact remains, however, that there is a greater number of safeguards and detailed factors in the installation and maintenance of oil-filled cable, requiring careful engineering attention. These are being reduced and simplified as experience is gained. It is largely a matter of education and training of field

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*Central Station Engg. Dept., General Electric Co., Schenectady, N. Y.

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forces in this new practise. Some special equipment is necessary for installation and maintenance. This consists of portable degasifier, vacuum pump and auxiliaries for short-field treatment of filling oil, joints, terminals, and other accessories. The special equipment is not expensive and represents a permanent investment, additional to the regular field equipment.

Those operating companies whose field forces now have the necessary experience and equipment handle oil-filled cable installations in a routine manner and without real difficulty.

FUTURE PROGRESS

The progress that has been made in the way of simplification and economy, will be dealt with by Mr. D. W. Roper.[5] Possible future progress will be briefly dealt with here.

The greatest progress seems to lie in the direction of reduction in insulation thickness. This is indicated by operating experience, laboratory study and field tests. Improved quality and more complete knowledge have recently allowed material reduction in standard thickness with resultant gain in economy. This forward step must be consolidated and confirmed by additional operating experience before the ultimate safe limit in insulation thickness can be determined. From what we know today, it would appear that because of absence of voids and ionization normal working voltage stress will not prove to be the limiting feature, but instead, ability to withstand transient voltages such as switching surges, arcing grounds, and lightning will determine ultimate safe thickness.

Guaranteed maximum temperature has already been increased from 60 to 65 deg. cent. and 70 to 75 deg. cent. Here again it is necessary to consolidate and confirm by operating experience. It would appear that insulation deterioration will not prove a factor in determining ultimate maximum temperature. This will, undoubtedly, be determined by the ability of the sheath to withstand expansional movement of the cable, and internal oil pressure.

PRINCIPLES

The principles of successful oil-filled cable practise are:

a. A stable, non-freezing oil of superior electrical properties. This oil should have predetermined viscosity characteristics that give assurance against void formation in the cable cross section and excessive loss of pressure along the feed channels in service.

b. A high quality wood pulp paper, compactly and uniformly applied, and of predetermined density.

c. Removal from the cable during manufacture, and from all accessories and fittings during installation, of all impurities such as moisture and gas (both free and in solution).

d. Maintenance of positive pressure inside the entire length of cable, and other parts of the oil system, at all times.

e. Never allow this oil pressure to exceed safe working limits, as determined by the mechanical strength of cable sheath and accessories.

The remaining part of this paper will deal briefly with those electrical, thermal, and physical characteristics that have the most to do with these principles. Scant space can be given to the usual electrical test properties.

The dielectric loss of oil-filled cable is quite low, 60-cycle power factor being in the order of 0.5 per cent at 80 deg. cent. There have been no indications of an increase in loss with time in service. Measurements seem to be of value only in checking uniformity in the factory and in determining reduction in current-carrying capacity at the higher voltage ratings. Dielectric loss causes a reduction of approximately 8 per cent in the current-carrying capacity of 132-kv. cable.

Many engineers feel that routine dielectric strength tests on samples could be dispensed with entirely. They are expensive and difficult to make and disclose very little of value. The breakdown strength of oil-filled cable on the standard 15-minute test is no better than that of solid cable having the same thickness of insulation and about half the voltage rating. Even on the standard 6-hour endurance test the breakdown strength of oil-filled cable is not much better than that of solid cable. It is only when this voltage application is extended into months and years that the real superiority of oil-filled cable is clearly shown.

DETERMINANT FACTORS AND CHARACTERISTICS

Power cable is subjected to continually changing temperatures in service consisting of daily load cycles superimposed upon seasonal cycles. Expansible oil reservoirs are connected to oil-filled cable at predetermined intervals to maintain pressure and take care of the volumetric changes caused by these fluctuations in temperature.

The contour of the cable run plays a very prominent part in determining the best location of reservoirs and stop joints, and the characteristics of the reservoirs necessary for maintaining oil pressure within prescribed limits. On long or steep hills it is necessary to insert oil stop joints at intervals to break up the hydrostatic head pressure. On level ground the location of stop joints (if any) is determined by maximum pressure drop along the feed channels.

In laying out the most effective and economical design of installation all of the principles and factors previously outlined must be taken into consideration. The primary characteristics that practically control the layout are:

a. Rate of expulsion and absorption of oil by the cable.

b. Oil-pressure drop along the feed channels.

c. Total expulsion or absorption of oil between the extreme limits of no-load winter temperature and full-load summer temperature.

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[5] For references see Bibliography.

d. Characteristics of available reservoirs.

Rate of Oil Expulsion and Absorption. When load is suddenly applied or dropped, oil is expelled or absorbed by the cable, the rate being governed by the rate of heating or cooling. Everything else being equal (and if no voids are formed) the expulsion and absorption curves are exactly alike. The rate increases to a maximum in a relatively short time and decreases to zero in a much greater time. Emanueli[1] dealt only with the maximum rate, this being the most important. In a later paper[2] oil expulsion is dealt with in greater detail.

Curves (*a*) and (*b*) in Fig. 5 of this paper[2] are representative of the hollow-core, 132-kv. cable installed in 1927 by our company. It is tentatively suggested on page 350 that the shaded area between curves (*a*) and (*b*) represented a brief, transient void formation. We have not since attempted to duplicate this test. Indirectly and comparatively, however, the evidence since obtained, has been confirmatory in every way. The theoretically calculated oil demand curve (*a*) has been proven correct and there is no reason for questioning the accuracy of the measured supply curve (*b*). In the light of later experience we believe that the void formation shown in Fig. 5 was caused by the following conditions:

a. The viscosity of the oil used at that time was higher than that of the improved oil used since.

b. The oil had been drained from the cable core after the initial impregnation treatment and the cable had stood for several weeks with this core filled with gas under pressure. Before test the cable had been re-impregnated with oil, the gas being removed by a relatively brief application of vacuum.

Subsequent tests and theoretical results indicate that the viscosity of this old oil could not have played anything more than a secondary part in this void formation. The ambient room temperature was 20 deg. cent. and similar tests made since with oil of both lesser and greater viscosity indicate that the ambient temperature would have to be much lower before the viscosity of this old oil would cause voids, *provided the dissolved gas content is of low value.*

The void formation indicated by Fig. 5 in this previous paper is insignificant from a practical standpoint. This is substantiated by the fact that 132-kv. cable of the type dealt with has operated successfully, and without signs of deterioration, for about four years. If progress is to be made, however, in the way of improved quality and reduction in insulation thickness these factors, no matter how insignificant they appear today, must be fully accounted for. We believe that the void formation mentioned was primarily due to dissolved gas content in the inner layers of insulation and that this condition was caused by the previous gas filling of the core. Measurements made since indicate that the dissolved carbon dioxide content of the oil in this cable, after uniform diffusion, was in the order of 8 to 10 per cent by volume at atmospheric pressure, room temperature. This is much below the saturation point of approximately 100 per cent.

Knowledge of the laws of gas absorption and diffusion in cable (and oil) as related to time, pressure, and temperature is still very meager and difficult to obtain. We have a good start in this direction, but there is still a great deal to be done in the way of confirmation and additional research. It is known that the amount of dissolved gas in oil is a direct function of pressure but increases more slowly with temperature, actually decreasing for some gases. The rate of diffusion is very slow in oil and still slower in cable. Diffusion increases with temperature. Saturation content varies widely with different gases, being low for hydrogen and nitrogen, about average for oxygen and high for carbon dioxide. The type of oil and, more particularly, its condition affect solubility. When more complete and detailed work is confirmed the results will undoubtedly be published.

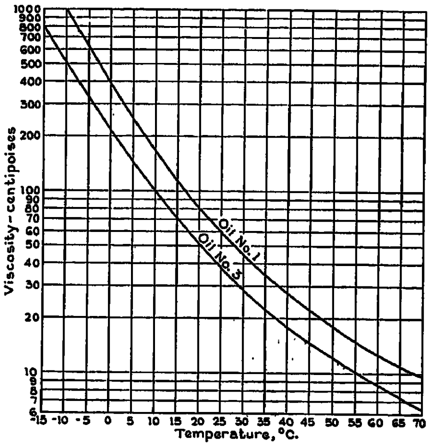

FIG. 1—VISCOSITY OF OIL

However, lack of accurate knowledge in this direction will not hold up progress in oil-filled cable development, since the principle of reducing gas content to a minimum, initially, and preventing further exposure is already firmly established. Real progress is in this direction.

This older cable has been referred to for the purpose of clearly bringing out the improvement that has since been accomplished. As far as can be determined, there is complete absence of void formation in the newer cable. These improvements involve an oil of more desirable characteristics, and methods of shipping and installing the cable while completely filled with oil. Exposure to gas absorption is reduced to a minimum and the dissolved gas content in the finished installation is only a fraction of that formerly experienced.

The viscosity of the old oil (No. 1) is shown in comparison with that of the new oil (No. 3) in Fig. 1. The freezing point of oil No. 3 is approximately – 40 deg. cent. and this safely allows exposure to severe outdoor winter temperature. At the same time, its viscosity is sufficiently high to avoid excessive loss of oil in case of leakage.

Fig. 2 shows typical oil supply and oil demand data for two sizes of the new, hollow-core, single-conductor cable. Space does not allow the inclusion of similar data for other sizes and types of single and three-conductor cable, but Fig. 2 is entirely representative. The measured oil supply and temperature after steady load is dropped are shown as plotted points. These measurements were made with two different oil pressures maintained in the hollow-core, as shown. Measurements of oil expulsion when the same load is applied were also taken. The two sets of measurements coincided so closely that the expulsion data will not be given. If voids had been formed when load was dropped the expulsion measurements should be greater than the supply during the first few minutes. They were actually either equal to, or slightly less. Also, if voids had been formed the supply measurements with lowest oil pressure should be less than the high-pressure readings. Fig. 2 would not indicate this to be so. The laboratory tests were conducted by Messrs. J. A. Scott and H. W. Bouseman, to whom grateful acknowledgment is made.

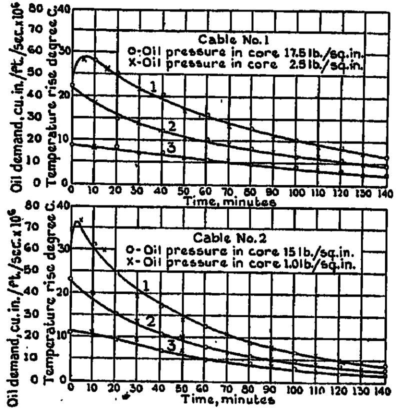

FIG. 2—OIL DEMAND AND SUPPLY AFTER DROPPING LOAD. THEORETICAL CALCULATIONS SHOWN BY FULL LINE CURVES. TEST RESULTS SHOWN BY PLOTTED POINTS

1. Oil demand and supply
2. Copper rise
3. Sheath rise

The theoretically calculated curves in Fig. 2 furnish a final check of this whole matter. It will be noted that there is almost exact agreement between theory and measurement. Other and similar laboratory measurements have fully confirmed the accuracy of the theoretical work. The calculation of temperature and oil demand is covered by formulas (1) to (7) in the Appendix.

Specifications and measured constants for the two sizes of cable considered in Fig. 2 follow:

Item	Cable No. 1	Cable No. 2
Clear inside diameter of core	0.500	0.500
Inside diameter of stranded conductor	0.600	0.600
Outside diameter of conductor	1.090	1.010
Copper cross section of conductor	600,000 cir. mils	475,000 cir. mils
Thickness of paper insulation	0.720	0.500
Thickness of lead sheath	0.156	0.141
Over-all diameter	2.842	2.300
Ratio oil to copper in core and conductor	0.99	1.15
Ratio oil to fiber in insulation	1.00	1.00
Thermal resistivity of insulation (C.G.S. units)	600	545
Emissivity of sheath (C.G.S. units)	1200	1010*
Thermal capacity copper per ft., (watt-second units)	328	260
Thermal capacity of oil in conductor per ft.	126	116
Specific thermal capacity of insulation (C.G.S. units)	0.360	0.360
Thermal capacity of sheath per ft.	382	275
Coefficient expansion copper	0.00005	0.00005
Coefficient expansion oil	0.00074	0.00074
Coefficient expansion fiber	0.00011	0.00011
Coefficient expansion sheath	0.000085	0.000085

*Note: Tarnished sheath

Fig. 3 shows the calculated temperature distribution of cable No. 1 from conductor to sheath when load is dropped. It will be noted that during the first 10 minutes when voids (if any) have a tendency to form there is little change in temperature of sheath and outer layers of insulation, but a relatively large change in temperature of conductor and inner layers of insulation. Consequently, when voids do form, they must first occur in, or near, this inner zone. It is for this reason that viscosity of oil does not play such a prominent part as dissolved gas content in Fig. 5 of the previous paper.[2]

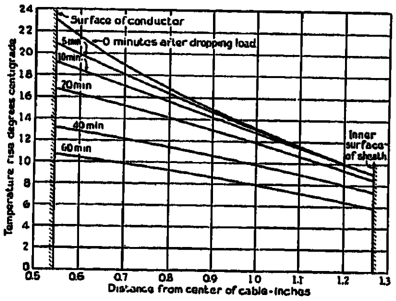

FIG. 3—TEMPERATURE DISTRIBUTION ACROSS THE INSULATION OF CABLE NO. 1 AFTER LOAD IS DROPPED. ISOLATED CABLE IN STILL AIR

Incidentally, Fig. 3 would indicate that an oil feed channel in the conductor is more effective than channels directly under the sheath. This is true only where there is danger of void formation. When this is eliminated, by methods already discussed, there does not appear to be any difference in the two methods of feed, judging from both theory and test.

Oil-Pressure Drop Along Feed Channels. Oil-pressure drop along feed channels and piping during periods of oil flow can be calculated with acceptable accuracy only where the inner surface is smooth and cylindrical and the rate of flow is less than turbulent. (See formula (**10**) in Appendix.) The surface of the hollow-core in cable No. 1 is not smooth, but is ridged, because of the spiraled supporting member. For this reason it is necessary to measure friction factor, *b*. For cables Nos. 1 and 2

$$b = \frac{0.00283\ Z}{d_1^4},$$

where d_1 is the clear inside diameter of core (0.5 in.). We have found that formula (**10**) holds with reasonable approximation for the type of core used in cable No. 1 if it is assumed that $d = 1.06\ d_1$. There are similar approximate methods for estimating the pressure drop in channel-type single-conductor and three-conductor cable, but here, it is even more necessary to confirm by actual tests.

Oil supply, (*a*), is distributed uniformly to the insulation by the feed channels. When factor (*a*) and the friction factor along the channels, (*b*) are known, the pressure drop can be determined by formula (**11**) in the Appendix. This formula was first developed by Emanueli,[1] who considered only the maximum value of (*a*). As will be shown, the pressure drop P_o is rarely, if ever, greatest when oil supply, (*a*), is at maximum value. Increase in oil viscosity accounts for this.

Total Oil Required. The total oil required is a direct function of cable length and the two extreme limits of temperature met with in service. These limits (for underground cable) are usually assumed as 0 deg. cent., no-load winter temperature, and 70 deg. or 75 deg. cent., full-load summer temperature. The method of estimating total oil is described in the Appendix. Usually, 40 per cent over and above the theoretical requirement is added to reservoir capacity as an emergency surplus and to safeguard against wrong adjustment of reservoir content and other possible discrepancies. The total oil requirement (theoretical plus 40 per cent) for typical single- and three-conductor cable varies from 0.5 gal. to 2.0 gal. per 100 ft. of cable, as determined by cable cross section, etc.

Reservoir Characteristics. The reader is referred to T. C. Aitchison's article[3] for details of design and performance. A previous article[4] also gives some general information regarding the three different types of reservoirs available and the methods of use. As indicated in these articles, the type *C C*, gravity-feed reservoir and the type *D C*, balanced-pressure reservoir have proved the most useful and desirable for oil-filled cable work. The present paper will, consequently, deal exclusively with these two types.

Types *C C* and *D C* oil reservoirs are identical in design and construction, with the exception that the outer rigid enclosing tank of type *C C* is open to the atmosphere through a breather, maintaining practically constant atmospheric pressure on the oil. The type *D C* reservoir, on the other hand, has a sealed gas-tight outer tank maintained under variable gas pressure. Both types follow the established principle of segregating and sealing off the cable oil system against exposure to gas or other impurities. The inner construction consists of a stack of disk cells, the walls of which are thin, corrugated, flexible metal diaphrams. The design is such that these diaphrams are supported in their fully-extended and fully-collapsed positions. This results in exceptional sturdiness and long life. The cells are connected in parallel by a manifold and are filled with degasified oil.

Type *C C* is known as an "atmospheric-pressure, gravity-feed reservoir," since it maintains constant atmospheric pressure and must be elevated above its surroundings for feed purposes. Type *D C* is used in those locations where elevation is undesirable or impractical and has proved very useful in eliminating expensive towers, sometimes necessary when type *C C* is used. It is known as a "balanced-pressure reservoir" because both the gas and oil volumes and pressures can be readily adjusted or balanced in such a way that reservoir units at different elevations can be made to work together in harmony and synchronism, each doing its fair share of the work.

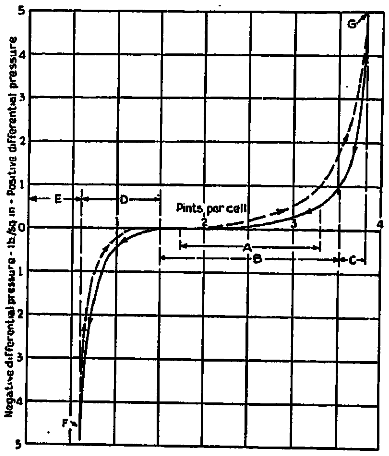

FIG. 4—DIFFERENTIAL OR DIAPHRAM PRESSURE CURVE OF TYPES *C C* AND *D C* RESERVOIRS, REPRESENTING DIFFERENCE OF GAS PRESSURE OUTSIDE AND OIL PRESSURE (AT CENTER LINE) INSIDE CELLS

A	Operating range from minimum cable temperature to maximum cable temperature
B	Full-rated capacity range of reservoir
C	Semi-idle range beyond rated capacity
D	Semi-idle range below rated capacity
E	Idle oil remaining in cells when totally collapsed
F	Totally collapsed position of cells
G	Totally expanded position of cells

The differential pressure or "back pressure" of the *C C* and *D C* reservoirs is shown in Fig. 4. This represents the difference in the oil pressure inside the cells (at center line of tank) and the gas pressure in the outer tank. When the cells are put through an extreme cycle of operation from completely-collapsed position under vacuum to completely-expanded position under six or more pounds positive differential pressure, and returned to their original collapsed position, the curves are in the form of a small hysteresis loop, as shown. In normal service, the cells are subjected to a much smaller total working range and this loop entirely disappears.

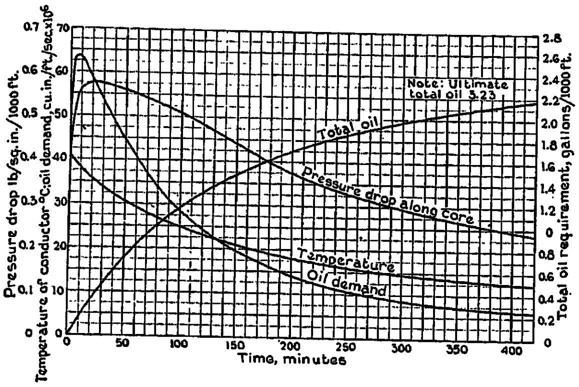

Fig. 5—Cable No. 1 Dropping Full Load in Winter with 0 Deg. Cent. Ambient Earth, Six Cables in Duct Bank

The reservoirs are adjusted in the field to always work over a limited part of the full-line curve, as shown in Fig. 4. It will be noted that the differential pressure is always positive over this normal working range. This avoids any danger of entrance of gas or moisture into the oil system through accidental leaks.

The *C C* cell stack fits closely in the outer tank and there is no surplus length to this tank. In the case of the *D C* units, however, there is extra length to the tank to give additional gas volume. This is necessary for maintaining gas pressure within desired limits. The gas volume can be readily adjusted either by adding an auxiliary gas tank for greater volume or introduction of waste oil for lesser volume. The pressure-volume characteristics of *D C* reservoirs can be readily calculated from the known laws of gases. See formula (9). This formula, of course, refers to gas pressure. The oil pressure can be obtained by adding the diaphram pressure given in Fig. 4.

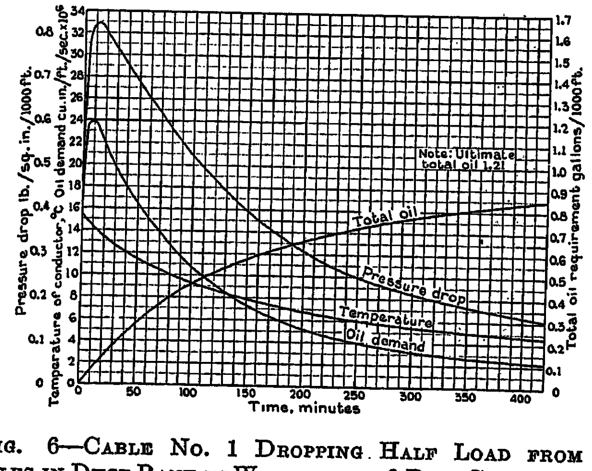

Fig. 6—Cable No. 1 Dropping Half Load from Six Cables in Duct Bank in Winter with 0 Deg. Cent. Ambient Earth

Other Factors and Characteristics

Thermal and Oil Feed Characteristics. Before an oil-filled installation can be properly laid out it is necessary to know the steady and transient thermal characteristics of the cable and surrounding duct structure. Characteristic curves for cable No. 1 are given in Figs. 5 and 6. It was necessary in calculating these curves to assume a typical cooling curve for the duct bank, as described immediately following formula (5) in the Appendix. If the characteristics of the duct bank are such that the exponential is greater or less than the assumed value 0.0000217 the curves in Figs. 5 and 6 do not hold. However, since we are largely concerned with the maximum values of oil supply and pressure drop, occurring in relatively brief periods of time, possible errors are not of great importance. In Figs. 5 and 6 it is assumed that load is dropped simultaneously from all of the cables in the duct bank. Also, short-circuited sheath-operation with 6½-in. flat spacing between six equally loaded cables and 0 deg. cent. earth ambient temperature are assumed as a "worst" condition.

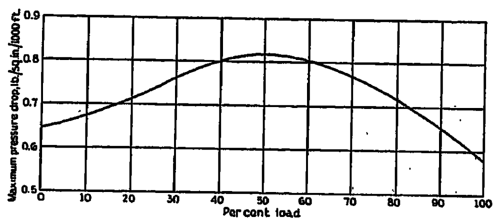

Fig. 7—Cable No. 1 Showing Maximum Pressure Drop Along Core in Winter for Different Loads

It will be noted that although the maximum rate of oil supply is less when half load is dropped (Fig. 6) the maximum pressure drop is greater than when full load is dropped (Fig. 5). Higher oil viscosity accounts for this. Fig. 7 shows the relation between percentage load and maximum pressure drop along the hollow core. Zero per cent load refers to dielectric loss only. It will be noted that 50 per cent load represents the worst or limiting condition. This limiting condition varies from 25 to 75 per cent of full load in different cases, depending upon cable size, minimum ambient temperature, and other conditions.

Feeder-Pressure Section. All of the necessary factors for cable No. 1 have been described and we are now in a position to lay out an actual installation. The contour of the duct run, spacing between manholes, dimensions of manholes and other practical considerations will determine the best and most economical layout. Pressure drop along the core, minimum oil pressure at high point, maximum pressure at low point and other factors will determine the location of stop joints and the type of oil feed for each section between stop joints. Space does not allow us to deal with an entire installation in detail. Instead, two typical sections will be selected for discussion.

First, assume a duct contour as shown in Fig. 8, with stop joints at positions 0 ft. and 3,000 ft. The sheath of cable No. 1 has no reinforcement and steady oil pressure at the lowest point (1,500 ft.) must not exceed 15 lb. per sq. in. Also it is desirable to avoid either a steady or transient oil pressure lower than atmospheric at any point in the oil feed system, consisting of reservoir cells, piping, stop joints and cable core. From the previous work it is known that the total rated oil capacity of the reservoir units for this length of cable is 25 gallons.

Balanced-pressure reservoir feed is obviously out of the question, since the hydrostatic pressure from position 0 to 1,500 ft. is already the full allowable 15 lb. If gravity-feed units (type *C C*) are placed at position 0 ft. and slightly above the stop joint, the minimum pressure in the cable core when full and half-load are dropped in the winter time is shown by curves (1) and (3). Both of these curves intersect the cable contour, and the oil system beyond these points of intersection would be at a pressure below atmospheric for several minutes. If the gravity reservoirs are raised to a sufficient height, as shown by curve (5), this condition could be avoided but this solution is not desirable since, instead of mounting the reservoir units directly in the manhole, it would mean an expensive reservoir housing above ground level. Also, safe working pressure of 15 lb. would be exceeded at lowest point of cable contour.

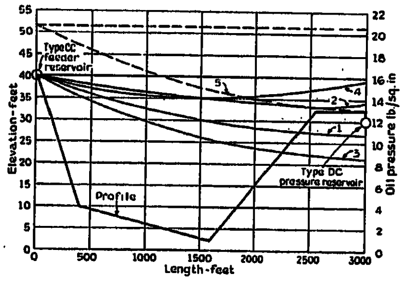

FIG. 8—TYPICAL FEEDER—PRESSURE SECTION CABLE NO. 1

Feeder reservoir rated 25 gal.

Pressure reservoir rated 3 gal. oil, 15 gal. gas

Curve 1—Pressure curve while full load is dropped in winter-time, feeding reservoir only

Curve 2—Same condition as Curve 1 with feeding-pressure reservoir combination

Curve 3—Pressure curve when half load is dropped in winter-time, feeding reservoir only

Curve 4—Same as Curve 3, with feeding-pressure reservoir combination

Curve 5—Same as Curve 3, shows height to which feeding reservoir must be raised to avoid vacuum at the far end under all conditions

The real solution is to leave the feeder units at stop-joint level and connect a small pressure reservoir (type *D C*) at low end of section. This pressure reservoir functions only during transient periods of temperature change and during these periods assists in maintaining cable core pressure within prescribed limits. Curves (2) and (4) with pressure reservoir connected show the improvement in pressure characteristics accomplished by the addition of this small unit. It will be noted that the limiting condition in this case, curve (2), occurs when full load is dropped, rather than half load. The reason for this is that dropping full load drains the oil from the small pressure reservoir more rapidly, with consequent reduction in its normal level of pressure, as shown.

A pressure reservoir required to meet the conditions in Fig. 8 would have a rated oil capacity of 3.0 gal. and a gas capacity, V_T, of 15 gal. The calculation of curves (2) and (4) involves such complicated differential equations that a step-by-step solution is resorted to.

It is known that, at the first instant, the pressure reservoir feeds half of the section. Assuming that it feeds half of the section for a short, but finite, length of time, the amount of oil which it feeds out and average loss of pressure can be calculated. The average distance fed during the time interval is then obtained from the formula:

$$x = \frac{l}{2}\left(1 - \frac{h - p}{a\,b\,l^2}\right)$$

b and a being respectively the average friction and oil demand during the period under consideration: p is the average pressure in the pressure reservoir. This value of x is less than half the length; accordingly, the output and pressure of the reservoir are corrected to take care of this change and x is re-calculated. Taking the value of x at the end of the period as a starting point, the above process is repeated; and it is continued until x becomes equal to zero. Then the pressure drop from the feeding reservoir over a distance $l - x$ is computed for each time interval.

Balanced-Pressure Section. On level ground, or where the profile of a given section is such that the feeder-pressure combination just described cannot be used without resorting to expensive mounting of reservoirs above ground level, the so-called balanced-pressure feed proves very convenient and economical. Fig. 9 shows a 2,500-ft. section of cable line having a contour that can be most conveniently taken care of by balanced-pressure feed. In all other respects the assumptions are the same as those outlined for Fig. 8. The total rated oil capacity is found to be 20 gal. This should be divided equally, one 10 gal., type *D C* unit being placed at each end, the relative elevations of these reservoirs being as shown in Fig. 9.

The gas capacity of these units and their initial volumetric and pressure settings are so selected that each reservoir takes care of exactly half of the cable section. Also, the pressure at the highest point in the oil system must never drop below 1 lb. above atmospheric, and the pressure at the lowest point must never exceed 15 lb. Reservoir characteristics that meet these conditions can be determined from formulas (8) and (9) in the Appendix. The calculations call for a gas volume, V_T, of 54 gal. for the lower reservoir and 41.6 gal. for the upper reservoir. The latter can be obtained either by using a shorter tank or by the more practical method of pouring 12.4 gal. of waste oil into the same size tank.

The pressure along the cable core under various limiting conditions is shown in Fig. 9. It will be noted that dropping either half-load or merely dielectric loss in the winter and full-load pressure in the summer represent the extreme limiting conditions.

It should be pointed out that for the type of oil feed considered in Fig. 9 exact balance of the reservoir units is not necessary within reasonable limits, and providing the gas content V_T is greater, but not less, than that called for by exact balance. For instance, instead of injecting 12.4 gal. of waste oil into the upper tank in Fig. 9 the original 54 gal. of gas capacity could be retained. The total pressure range would thereby be reduced but the behavior of pressure drop along the core would be complicated and would have to be determined by the step method already discussed.

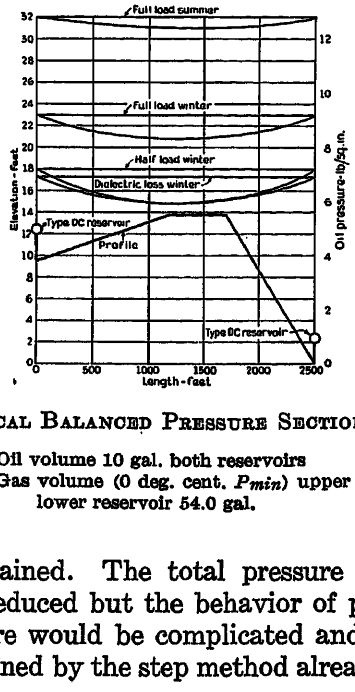

FIG. 9—TYPICAL BALANCED PRESSURE SECTION CABLE NO. 1

Reservoir Data: Oil volume 10 gal. both reservoirs
Gas volume (0 deg. cent. P_{min}) upper reservoir 41.6 gal.
lower reservoir 54.0 gal.

Other Systems of Oil Feed. Some additional details regarding balanced-pressure feed, as related to three-conductor and channel-type single conductor cable will be found in a previous article.[3] Space does not allow us to deal with other systems of oil feed. Some of these systems are briefly outlined in a previous article.[4] Additional details will be included in an article[6] soon to be published.

There are many factors that determine the best and most economical system of oil feed and general layout of oil-filled cable installations. The best system might vary anywhere from a stop joint and reservoir in every manhole, where very rugged contour is encountered, to complete exclusion of stop joints on level ground. Generally speaking, the use of stop joints should be reduced to a minimum. Stop joints should not be used merely for segregation, since the advantages gained are nullified by the additional expense and the limited amount of reservoir oil available for emergency use in case of accidental leakage. Segregation, where actually required, can be obtained by safer and more economical methods.

Strength of Lead Sheath. The integrity of the sheath is a very important feature of oil-filled cable practise. We have given a great deal of time and thought to this problem. Commercially pure lead and alloys of lead in the form of ordinary sheathing with and without reinforcement and special double sheathing with reinforcement have been investigated and used in service. With ordinary sheathing without reinforcement it has been found that safe continuous oil pressure is limited to approximately 15 lb. per sq. in., and with reinforced sheathing, to about twice this value. A very comprehensive series of tests on lead and lead alloy sheathing is still being continued. Elongation and bursting strength as a function of time and temperature are fairly well established. Space limitations prevent publication of results at the present time.

ACKNOWLEDGMENT

The authors wish to emphasize that the development of oil-filled cable, as outlined in this paper, has involved extensive cooperation of a number of individuals. We wish that each could be given full and merited credit, but this is impossible. Outstanding contributions of thought and effort have been made by Messrs. W. C. Hayman, G. M. J. Mackay, R. H. Park, J. A. Scott, C. A. Piercy, E. D. Eby, E. L. Crandall, T. C. Aitchison, H. W. Bouseman, L. L. Phillips, H. P. Broderson and V. A. Sheals.

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Appendix

In the present appendix, it is proposed to give some of the formulas used in the calculation of oil-filled cable characteristics. Space does not permit the development of these formulas; the reader is referred to an article[6] if such information is required.

Before oil demand calculations can be made, it is necessary to compute the thermal transient:

$$T = \sum A_n F\,(u_n x)\,\epsilon^{-u_n{}^2 t/p'q} + T_d\,\epsilon^{-\alpha t} + T_o \qquad (1)$$

In the foregoing equation

$$A_n = \frac{\dfrac{p'\,\Delta_1\,\Delta_2}{\pi}\left[\dfrac{W_c}{u_n}\,\dfrac{\Delta_1}{r} - W_s\,\Delta_2\right]}{[\{M_2\,(u_n R)^2 - N\}^2 + (1 + 2\,M_2)\,(u_n R)^2]\,\Delta_2{}^2 + [2\,M_1 - 1 - M_1{}^2\,(u_n r)^2]\,\Delta_1{}^2} \qquad (2)$$

$$F\,(u_n x) = J_o\,(u_n x) - K_n\,Y_o\,(u_n x) \qquad (3)$$

$J_o\,(u_n x)$ and $Y_o\,(u_n x)$ being the Bessel functions of the first and second kinds, and of zero order; see reference (10).

K_n and u_n are given by the following equation:

$$K_n = \frac{M_1\,u_n\,r\,J_o\,(u_n r) - J_1\,(u_n r)}{M_1\,u_n\,r\,Y_o\,(u_n r) - Y_1\,(u_n r)}$$

$$= \frac{[M_2\,(u_n R)^2 - N]\,J_o\,(u_n R) + u_n R\,J_1\,(u_n R)}{[M_2\,(u_n R)^2 - N]\,Y_o\,(u_n R) + u_n R\,Y_1\,(u_n R)} \qquad (4)$$

The denominators of the two fractions in equation (4) are Δ_2 and Δ_1 respectively (see symbols). The summation in equation (1) is taken over the roots of equation (4).

Also,*

$$M_1 = \frac{Q_1}{2\,\pi\,q\,r^2}; \quad M_2 = \frac{Q_2}{2\,\pi\,q\,R^2}; \quad N = \frac{p'}{2\,\pi\,R_{ths}} \qquad (5)$$

α is a quantity dependent on the construction of duct bank, number of loaded cables in it, etc. For average conditions, it may be taken as 0.0000217, if t is measured in seconds.

Equation (1) gives the temperature T at any distance x from the center of the cable at any time t. Equations (1) to (5) are also useful in calculating other thermal effects, such as short-circuit heating and overload duty cycles.

The oil demand of a cable is equal to the rate of contraction of the component parts of the cable when load is dropped. This may be determined by using the following equation:

$$a = 12\,\alpha\,T_d\,(\eta_i V_i + \eta_o V_{oc} + \eta_c V_c + \eta_o V_{os} - \eta_1 V_s)\,\epsilon^{-\alpha t}$$

$$+ \sum \epsilon^{-u_n{}^2 t/p'q}\,\frac{12\,u_n{}^2\,A_n}{p'\,q}\Bigg[\frac{2\,\pi\,\eta_i\,R}{u_n}\Bigg\{\frac{M_2\,(u_n R)^2 - N}{u_n R\,\Delta_1}$$

$$- \frac{u_n\ r\ M_1}{u_n R\,\Delta_2}\Bigg\} + \frac{\eta_o V_{oc} + \eta_c V_c}{u_n r\,\Delta_2} + \frac{\eta_1 V_s - \eta_o V_{os}}{\Delta_1}\Bigg] \qquad (6)$$

The total oil requirement of the cable over the temperature range $T_c - T_o$ may be obtained by integrating this equation between the limits $t = O$ to $t = \infty$. It may also be obtained more readily from the following equation:

$$D = 12\left[\begin{array}{l}(\eta_c V_c + \eta_o V_{oc} + \eta_i V_i)\,(T_c - T_o) \\ \qquad + (\eta_o V_{os} - \eta_1 V_s)\,(T_s - T_o) \\ + \dfrac{p'\,W_c\,\eta_i}{2\,\pi}\{(V_i/2) - V_s \log_e (R/r)\}\end{array}\right] \qquad (7)$$

If the total oil requirement over the entire yearly temperature range is wanted, it may be obtained from equation (7) by writing T_o equal to the minimum winter earth temperature, T_c equal to the maximum allowable copper temperature, and T_s to the temperature of sheath when copper temperature is T_c.

The reservoir requirement in gallons per 1,000 ft. is equal to $\dfrac{1.4\,l\,D}{231}$, assuming that a 40 per cent surplus is allowed. To this should be added the oil contraction of joints, terminals, reservoirs and piping. The total volume of oil thus computed is called $2\,V_{max}$.

If a pressure reservoir is to be used, the gas volume V_{T} at temperature T_{min} and pressure P_{min} must also be calculated:

Lower Reservoir

$$P_{min}\,V_{\mathrm{T}1} = \frac{P_{max}\,(V_{\mathrm{T}1} - V_{max})\,(T_{min} + 273)}{273 + T_{max}} \qquad (8)$$

Upper Reservoir

$$(P' - h)(V_{\mathrm{T}2} - V') = \frac{(P'' - h)(V_{\mathrm{T}2} - V'')(T_{min} + 273)}{273 + T_{max}} \qquad (9)$$

Intermediate reservoirs, where such are used, may be calculated as "upper" reservoirs from formula (9), using the proper value of h, provided the reservoir system is so balanced that each reservoir feeds its proportionate length of cable at all times. This will be true of a balanced system, but not of an unbalanced system.

The pressure drop in a pipe with a smooth cylindrical surface may be calculated from the equation:

$$p_1 = 2\,\frac{q'\,f\,l_1}{\pi\,g\,d^4} \qquad (10)$$

The pressure drop in the core of a hollow core cable at any distance x_o from the feeding point may be calculated from the equation.

$$p_o = 2\,a\,b\,(l\,x_o - x_o{}^2/2) \qquad (11)$$

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*This notation is the same as used by K. W. Miller in his partial solution of this problem. See discussion of paper, Bibliography reference (1).

where,

$$b = \frac{0.8 f}{\pi g d_1^4} \tag{12}$$

List of Symbols

a = oil demand of cable, cu. in. per ft. per sec.

b = friction factor for hollow core cable.

d = inside diameter of smooth cylindrical pipe, inches.

d_1 = inside diameter of spiral in cable core, inches.

D = total oil requirement of cable, cu. in. per ft.

f = friction coefficient in smooth pipe $= 0.00358\, Z$.

g = gravitational constant = 32.2 ft. per sec. per sec.

h = difference in elevation between upper and lower reservoirs, expressed in lb. per sq. in.

l = length of cable section, feet.

l_1 = length of pipe, feet.

p' = thermal resistance of cable insulation, deg. cent. per watt per in. thickness per 12 sq. in.

p_o = pressure drop in core of cable, lb. per sq. in.

p_1 = pressure drop in a smooth cylindrical pipe, lb. per sq. in.

P' = gas pressure in the lower reservoir at no load, lb. per sq. in. absolute.

P'' = gas pressure in lower reservoir at full load, lb. per sq. in. absolute.

P_{min} = minimum permissible pressure of gas in lower reservoir, lb. per sq. in. absolute.

P_{max} = maximum permissible pressure of gas in lower reservoir, lb. per sq. in. absolute.

Q_1 = thermal capacity of conductor, including oil in strands and core, watt-sec. per ft. per deg. cent.

Q_2 = thermal capacity of sheath, armor, and oil in channel space under sheath, if any, watt sec. per ft. per deg. cent.

q' = rate of flow of oil through pipe, cu. in. per sec.

q = thermal capacity of insulation, watt-seconds per deg. cent. per 12 cu. in.

r = outside radius of cable conductor, inches.

R = inside radius of cable sheath, inches.

R_{ths} = thermal resistance of sheath surface, in thermal ohms per ft.

t = time, in seconds.

T = temperature, rise above duct air in deg. cent. of a point at distance x from center of cable, at time t.

T_c = temperature rise above duct air of cable conductor at beginning of cooling, deg. cent.

T_s = temperature rise above duct air of sheath at beginning of cooling, deg. cent.

T_d = temperature rise above earth ambient of duct air at beginning of cooling, deg. cent.

T_o = ambient temperature, (of earth, air, or water, depending on operating condition).

T_{max} = maximum temperature of gas in reservoir, deg. cent.

T_{min} = minimum temperature of gas in reservoir, deg. cent.

V_c = area of copper in cable conductor, sq. in.

V_{oc} = area of oil in cable core and strand space, sq. in.

V_i = area of cable insulation, sq. in.

V_{os} = area of oil in channel space under sheath, sq. in.

V_s = total area inside cable sheath, sq. in.

V_{max} = one half of the total oil requirement of section of cable, including surplus, gallons.

V' = surplus oil in reservoir at lower end of operating range, gallons. (This refers to working surplus only.)

V'' = V' plus expulsion of oil from cable at maximum full load temperature gallons.

V_{T1} = volume of gas in lower reservoir, at pressure P_{min}, and temperature T_{min}, gallons.

V_{T2} = volume of gas in upper reservoir, at pressure $P_{min} - h$, and temperature T_{min}, gallons.

W_c = sum of copper loss and dielectric loss of cable, watts per ft.

W_s = sum of sheath loss and armor loss of cable, watts per ft.

x = distance from center of cable, inches.

x_o = distance from feeding point on oil-filled cable line, ft.

Z = viscosity of oil, centipoises.

α = multiplying factor in duct cooling exponential; average value 0.0000217.

Δ_1 = $[M_2 (u_n R)^2 - N]\, Y_o (u_n R) + u_n R\, Y_1 (u_n R)$ (see equation (4)).

Δ_2 = $M_1 u_n r\, Y_o (u_n r) - Y_1 (u_n r)$ (see equation (4)).

ϵ = base of Naperian logarithms, = 2.7183....

η_c = coefficient of expansion of copper (volumetric) per deg. cent. = 0.00005

η_i = coefficient of expansion of insulation (volumetric) per deg. cent. = 0.000425.

η_l = coefficient of expansion of lead (volumetric) per deg. cent. = 0.000085

η_o = coefficient of expansion of oil (volumetric) per deg. cent. = 0.00074.

Discussion

For discussion of this paper see page 1447.

Oil-Filled Cable and Accessories

BY R. W. ATKINSON* and D. M. SIMMONS*
Fellow, A. I. E E. Fellow, A. I. E. E.

Part I

A COMPLETE OIL-FILLED CABLE SYSTEM

Introduction. The term "oil-filled," as applied to impregnated paper cables is ordinarily understood to indicate a cable in which the compound is of such viscosity as to be fluid at all operating temperatures. When such a cable is so constructed as to permit free passage for the oil longitudinally and radially and is connected to a suitable oil supply it will remain completely filled with saturant at all points, throughout all temperature and load cycles.

Under careful attention the modern high-grade solid or hard compound cable may receive a thorough initial impregnation. It is generally agreed, however, that under repeated load and temperature cycles, the expansion of the sheath tends to the formation of "voids" or bubbles in the insulation, leading to ionization, deterioration, and ultimate failure. Provision against this tendency necessitates conservative current ratings. This type of limitation is inherent in the use of saturants of high viscosity and of completely closed lead sheath and joints, and becomes increasingly important with increasing wall thickness, *i. e.*, with increasing voltage rating. The oil-filled cable, by providing for a free ebb and flow of saturant at all times, removes the danger of bubble formation, thus permitting thinner walls, higher temperatures, higher voltages and current ratings.

Cable engineers both in this country and in Europe have long recognized the theoretical advantages of the oil-filled principle, but the first attempt to realize these advantages on a large scale was the extensive installation of General Electric Co. and Pirelli & Co. oil-filled cables in New York and in Chicago about four years ago. The outstanding electrical performance of these installations fully confirmed the early expectations. While the great cost and the complicated operations connected with their installation prevented the immediate wide-spread adoption of oil-filled cable, this performance acted as an intense stimulant to the improvement and simplification of that system, some of the results of which have been and are being described by their makers.[1,2,3,4] It also produced increased concentration on a parallel development which had been proceeding along somewhat different lines, and which has resulted in the system to be described in this paper. This system has been planned from its inception with the aim of approximating the simplicity of the installation of the ordinary type of cable. In its present form, it has made notable progress towards accomplishing this aim, and now also has a background of completely successful practical experience.

General Features. Fundamental features about which this system has been built are:

1. Shipment of cable filled with oil, and without field evacuation and reimpregnation.
2. Stop joints of moderate size and cost, and a rapid and reliable technique of installation, making practicable oil feed lengths as short as desired.
3. Reliable oil feed system, including compact designs of expansion oil reservoir with oil volume indicator, and an automatic signal system designed to give to oil-filled cable the same superiority over solid type cable in freedom from service failures due to mechanical causes that it now enjoys with respect to electrical trouble.
4. For multi-conductor cable provision of oil channels in the filler spaces, making the system equally applicable to single- and three-conductor cable.

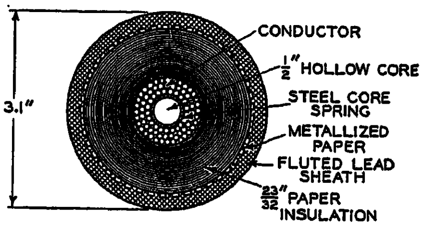

FIG. 1—CROSS SECTION OF 132-KV. SINGLE-CONDUCTOR, HOLLOW CORE, OIL-FILLED CABLE WITH 23/32-IN. INSULATION AND FLUTED LEAD

It is the purpose of this paper to give only a very brief outline of the general manner in which these important developments have been accomplished.

The Cable. A cross-section of single-conductor cable for 132-kv. service is shown in Fig. 1. An oil channel is provided in the center of the conductor which is stranded in the usual manner on an open spiral of flat steel. In some cases this is also supplemented by a number of longitudinal slots in the inner face of the sheath. The cable shown is of type *H* construction, having a layer of metal foil between insulation and sheath.

The cable is leaded before drying and impregnation, both of which processes are carried out completely in the factory. The leaded cable is placed in an oven equipped to maintain uniform temperature throughout. Special end seals are supplied which make it possible to apply vacuum or pressure independently to the hollow core and to the space between the paper insulation and the lead sheath, and to admit carbon dioxide or hydrogen after the air is exhausted. Power-factor and insulation resistance measurements are made in the usual way during the drying period. The removal of moisture and gas is accomplished by use of high vacuum pumps capable of producing a vacuum of a few microns absolute pressure. When the electrical measurements and vacuum attained in the cable show the cable to be completely dry, dried, degasified oil is admitted to the hollow core. After the cable is completely filled, a considerable quantity of oil is permitted to flow through. When the fluted lead is used, this procedure makes it possible to flush out completely any gas or vapor occluded by the paper, and to carry it away in the oil as it flows through. This insures the elimination of gas and moisture to the highest possible degree. The possibility of maintaining, throughout shipment, installation, and jointing, the high quality of insulation acquired in the factory, is realized through the use of a transportation reservoir maintaining within the cable sheath a pressure slightly above atmosphere at all times during shipment and installation.

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*General Cable Corporation, New York, N. Y.

1. For references see Bibliography.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

The Stop Joint. The development of a reliable and comparatively inexpensive stop joint, moderate in size and simple to install, is a most important feature of this system. The availability of such a joint makes it practicable to sectionalize the cable as regards oil supply to any extent desired. Independent supply for relatively short sections makes possible the use of smaller reservoirs requiring a minimum of manhole space, contributes to increased reliability, lessens cost of possible cable trouble, and permits lower hydrostatic pressures.

This joint, utilizing the condenser principle, involves radical departures from classical methods of jointing and its strength as indicated by the test results given in Part II, has exceeded anything previously accomplished. A discussion of certain details of theoretical design (which are equally applicable to stop joints and to non-stop joints) will be given separately in Part II.

The advantages of this new type of joint are many. The condenser unit which comprises the complete assembled joint insulation is dried, impregnated, and its casing filled with oil and sealed, and the completed unit tested before leaving the factory. This construction results in great saving of time and of labor in the making of a joint in the field, the operation being practically limited to the assembly of mechanical fittings and the making of wiped joints. The reduction of time and area of exposure of the cable insulation during jointing is also noteworthy. Also of special interest is the moderate space requirement of the completed joint as compared with stop joints of equal rating and earlier design. Stop joints of this type installed on a commercial 132-kv. line in Chicago early in January of last year were approximately 8⅝ in. diameter by 61 in. long. On a later experimental installation at the same voltage, stop joints 5¾ in. diameter by 55¼ in. long were used, and the perfect operation of these joints together with laboratory tests indicate possibility of still further reduction.

The "stop" feature is provided by a simple enclosure (or "stop tube") applied over one or both cable ends. The body of this tube is of rigid insulating material and is cemented into a metal sleeve at each end. A special connector thimble is used which forms an oil-tight cap over the hollow core conductor and which is sealed to the adjacent brass sleeve on the stop tube by means of a gasket joint. A thin solder wipe is made between the sleeve on the other end of the stop tube and the cable sheath, thus completely closing off the end of the cable. Threaded openings are provided through the brass sleeves for the purpose of evacuation and oil filling of the stop tubes. These openings may be sealed off at the time of installation, or may be used for connection to the oil circulating system, thus providing an extremely flexible arrangement by means of which the joint sleeve itself and the adjacent cable sections may be isolated from each other or connected to the oil feed in any desired combination. A joint of similar design is readily adaptable to three-conductor cable.

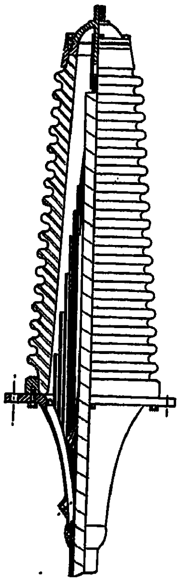

FIG. 2—BARRIER TYPE TERMINAL ARRANGED FOR OIL IMMERSION

Terminals. Two types of terminal have been developed for systems in the higher range of voltage. Fig. 2 represents an oil-filled terminal of the barrier type arranged for terminating a cable in oil-filled apparatus such as a transformer. The barrier construction which is illustrated and fully described in a previous article has been used for a number of years in connection with cables of the solid type insulation for voltages up to 66 kv. on a large number of installations, and on experimental lines up to 132 kv. In all of these installations no case of electrical failure has been reported.

A terminal of the same general design as the condenser joint is discussed in detail in Part II and illustrated in Fig. 12. For outdoor use the design as shown is supplemented by a protective porcelain bushing.

Oil Supply. Fig. 3 shows an oil reservoir in which the expansible element is a single-unit metallic bellows. This contains the oil and is, in turn, enclosed in an outer gas tight steel casing. The changes in the volume of the oil in the cable during temperature cycles are compensated for by the expansion and contraction of the bellows, thus insuring that the pressure in the cable will at all times be within safe limits. In order to insure prompt and positive return of oil to all parts of the cable when contraction occurs, a small pressure above atmosphere (from 15 to 25 lb.) is maintained. This pressure can be produced by various means such as gas pressure in the outer casing, weights, springs, or combinations of these. With large diameter bellows, gas is found to be the most convenient. Supplementing the gas, a weight or a relatively light compression spring, as shown in Fig. 3, is used to overcome the slight inherent stiffness of the bellows. This insures that the oil pressure will always be higher than the gas pressure so that in case of a bellows leak, the oil will leak outward into the gas instead of gas passing into the oil, and, in addition, the bellows will be gradually compressed to the point where the low volume contactor will operate.

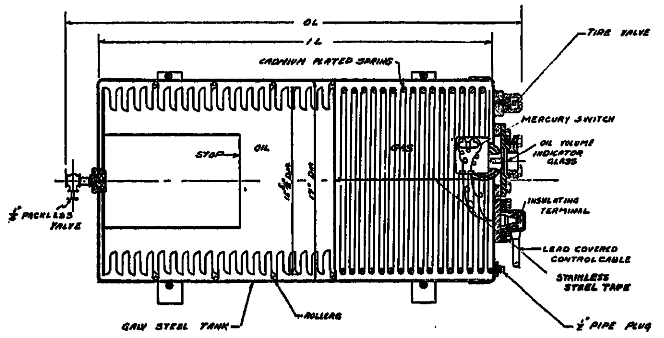

FIG. 3—PRESSURE TYPE VARIABLE VOLUME OIL RESERVOIR

The advantages of the single bellows type expansible unit in ease of assembly, and in the simplicity of design required for oil volume indicator and signal device which can be operated by the free end of the bellows will be evident, and cyclic life tests on bellows of this type up to 16 in. diameter indicate that they will have indefinitely long life under operating conditions.

Fig. 4 gives a diagrammatic view of the principal elements of the oil feed system. Suitable valves are provided for isolating individual cables or reservoirs, and for manifolding the oil systems of the three individual cables as desired. Under some conditions, an oil pipe line may be extended the entire length of the system and manifolded to individual cables or reservoirs.

In addition to the direct reading gages which are provided to indicate both oil volume and oil pressure, automatic alarm signals may be used to give warning of either low volume or low pressure. The volume indicators are operated by mechanical connection to the bellows and the pressure indicators are connected directly on the oil feed lines (see Figs. 4 and 5). Alarm signals are transmitted through mercury tube contactors which operate an annunciator installed in any convenient central location. All contactors are connected in parallel and in case of low oil volume or low pressure the particular cable section involved is readily determined by opening the switch in the annunciator circuit and balancing the simple bridge shown in Fig. 5.

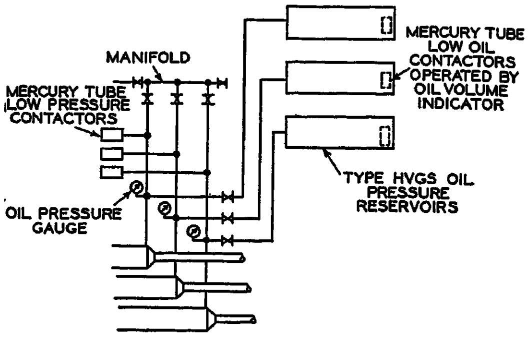
MANIFOLD
MERCURY TUBE LOW PRESSURE CONTACTORS
OIL PRESSURE GAUGE
MERCURY TUBE LOW OIL CONTACTORS OPERATED BY OIL VOLUME INDICATOR
TYPE HVGS OIL PRESSURE RESERVOIRS

FIG. 4—LAYOUT OF RESERVOIR SYSTEM

This whole oil supply and signal system is very simple, reliable, and sturdy. Whereas, with solid cables, external mechanical causes have resulted in more service failures than have electrical causes, the means here described provide an assurance against most forms of such interruptions on oil-filled cables comparable with the assurance provided against electrical failures by the perfect electrical performance oil-filled cables have so far shown.

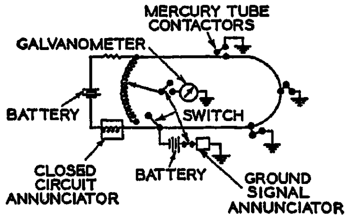

FIG. 5—ELECTRIC SIGNAL SYSTEM AND BRIDGE FOR LOCATING LEAKS

Service Performance. Although the number of complete installations of oil-filled cable systems in commercial operation is still relatively small, these installations nevertheless, in conjunction with experimental studies both in this country and in Europe, have clearly shown a very notable superiority over the older types of cable.

The remarkable performance of the 132-kv. cable system is well known and is indicative of the equal satisfaction which can be expected on cables for lower voltages with reduced insulation thicknesses. Even now in addition to several smaller installations there is in operation about a mile of three-conductor 33-kv.

cable of the oil-filled type installed in Los Angeles, California.

The reduction in insulation wall thickness possible in oil-filled cable is especially noteworthy. The experience with 132-kv. cable is a sufficient example. Cable of the type described here, now in operation in Chicago at this voltage, has a wall thickness of 23/32 in., which is less than used heretofore on any 66-kv. cable having solid insulation. Experimental cables of this type with wall thicknesses of 17/32 in. and even 13/32 in. have been connected to 132-kv. power lines at Chicago since the summer of 1930, without trouble, indicating the apparent reliability of this type of insulation at values of stress far beyond any heretofore possible. Other experimental cable for 220-kv. service has now been manufactured and preliminary tests including a voltage test in 30-sec., 25-kv. steps, up to 725 kv. without failure, indicate that it should be entirely adequate for operation at this voltage.

Part II

CONDENSER JOINTS AND TERMINALS

Introduction. With each step in the improvement of cable design, and with the constantly increasing strength of cable insulation, the problem of providing joint and terminal construction which will be as strong as the cable itself has been increasingly difficult. The advent of the oil-filled cable with its large increase in voltage for a given insulation thickness has made the situation still more acute.

It is the purpose of this section to describe very briefly a new form of terminal and joint using the condenser principle which has greatly simplified the problems of joint and terminal design. This type of construction was first developed in connection with tests to destruction on short cable samples to provide terminals which would prevent longitudinal discharges within the terminal structure and insure that ultimate failure would occur in the cable itself and not in the terminal. One characteristic of paper insulation which has an extremely important influence on joint and terminal design is its low dielectric strength longitudinally in comparison with its radial strength. This point, though recognized, has been given very little previous study. Some data recently obtained on the longitudinal strength will therefore be given in this paper.

Problems of Terminal Design. In order to have in mind the problems to be met, we may review the conditions which exist where a cable terminates. Since practically all high-voltage cable now made is either single-conductor or of type *H* multi-conductor construction, and since the individual conductors of a type *H* cable are electrically equivalent to single-conductor cables, for the sake of simplicity, this discussion is confined to cables of the latter type.

Fig. 6 shows diagrammatically a terminal in its simplest form. Here the termination consists in the mere removal of a portion of the cable sheath. The longitudinal distribution of voltage which results in this case is plotted in Fig. 6. The slope of the curves at any point in each case shows the stress at the corresponding point along the surface of the insulation. It is evident that near the end of the lead sheath there is in both the paper insulation and the surrounding air, a high concentration of longitudinal stresses. In addition it is obvious that even greatly increasing the length of the terminal is of little avail in mitigating stress conditions at the sheath edge. The conditions as illustrated in Fig. 6 are well known and result from the elementary relations between the capacities to the conductor and to the sheath of the various points along the surface of the exposed insulation. There are then two difficulties to be taken care of by an adequate terminal design:

The stress in the air surrounding the terminal, which has comparatively low dielectric strength.

The longitudinal stress in the paper which has a low strength in this direction.

Various methods have been devised to relieve the stress in the air, such as building up with insulation around the end of the sheath, or surrounding the exposed end of the insulation with insulators or metal cones filled with oil or other insulating compound. But when the difficulty with the breakdown of the air is reduced or overcome, we are immediately confronted by longitudinal discharges in the cable insulation itself.

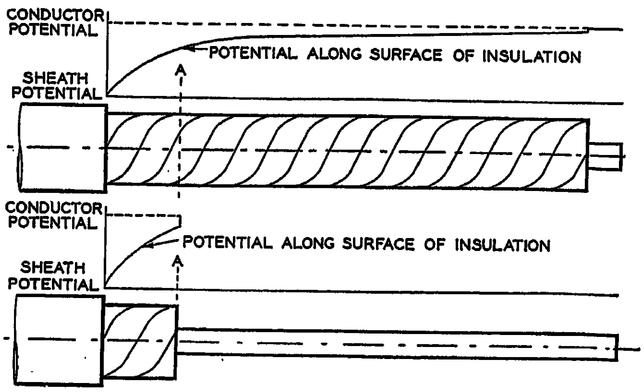
CONDUCTOR POTENTIAL
POTENTIAL ALONG SURFACE OF INSULATION
SHEATH POTENTIAL
CONDUCTOR POTENTIAL
POTENTIAL ALONG SURFACE OF INSULATION
SHEATH POTENTIAL

FIG. 6—CABLE TERMINAL IN SIMPLEST FORM, SHOWING LONGITUDINAL DISTRIBUTION OF POTENTIAL

One partial solution by means of which the longitudinal stresses in the vicinity of the termination of the lead sheath are somewhat redistributed and one which is in extensive use at the present time, consists of a flaring ground shield at the end of the sheath. This principle has been applied in several varied forms. One method which was first used successfully in laboratory tests and later developed for use in commercial terminals employs a spun-copper cone in which are mounted a series of concentric tubes of insulating material which surround the exposed portion of the insulation and which are filled with insulating oil. Sometimes this is accomplished by building up a tapering surface of varnished cloth or paper and the resultant taper shielded with a metallic braid, or by the method described by Simmons[5] in which a cone is formed during the application of the insulation. Clearly, to solve the problem, there is required some method of controlling the distribution of the longitudinal stresses so as to make them substantially uniform throughout the length of the terminal.

Resistance Type Terminals. A method of accomplishing this which has been used to some extent for test terminals makes use of a semi-conducting material surrounding the end of the cable and having sufficiently low resistance to permit a current flow large enough to control the potential distribution by resistance drop. With direct current or with moderate alternating potentials this can be used satisfactorily. With alternating current, however, in order to control the potential distribution effectively, the current flowing through the resistance must be large compared to the capacity or charging current through the insulation. Consequently, for the higher voltages, say above 100 kv., serious difficulties are encountered in taking care of the heating due to the $I^2 R$ loss, and for the still higher voltages this construction becomes entirely impracticable.

Condenser Type Terminals. The principles by which the final solution has been obtained have long been partially recognized and previous attempts have been made to utilize some of them. Since such designs have been only partially successful due to a failure to meet certain fundamental requirements, no detailed description will be made. The final solution may be explained with the aid of an illustration from a very early partial solution illustrated in Fig. 7. This represents a cable end upon which is mounted a series of conducting disks or plates insulated from the conductor and from each other. Consider the potential of the plate adjacent to the one touching the sheath. Following the same reasoning used with reference to Fig. 6, it is evident that this plate will take a potential near to that of the sheath. Also the potential difference between these plates can be brought to any desired small amount by sufficiently increasing their size. The dimensions required to produce an even distribution of potential between these plates may be determined by a fairly simple mathematical analysis. In general, therefore, the arrangement of Fig. 7 can accomplish the desired redistribution of potential both along the surface of the conductor insulation and through the air. This scheme was developed independently by several different engineers. It was suggested by C. W. Davis and actually applied usefully in our Pittsburgh laboratory in 1914. It has also been well described in a recent paper by Farmer.[6]

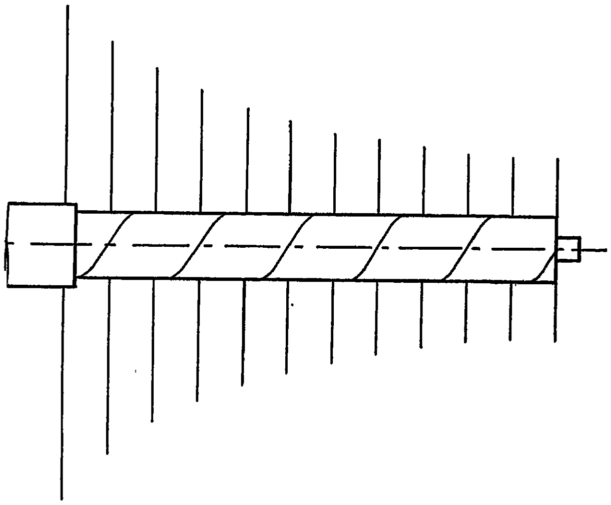

FIG. 7—TERMINAL WITH LONGITUDINAL DISTRIBUTION CONTROLLED BY METAL DISKS

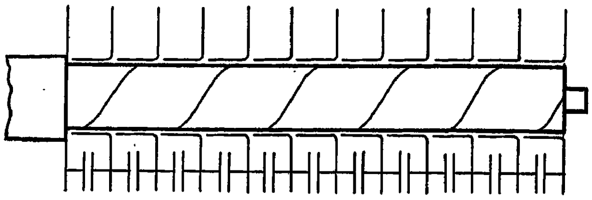

FIG. 8—DISKS SUPPLEMENTED BY PROPERLY PROPORTIONED CONDENSERS

There are two difficulties with the type of terminal illustrated in Fig. 7. In the first place, it is apparent that there is a concentration of stress at the inner edges of the metal plates. In the second place, the physical dimensions required with this type of terminal to produce requisite capacity between plates are prohibitively large except for terminals of only a few inches in length and thus adapted only for relatively low voltages.

The arrangement of Fig. 7 is then, in spite of the difficulties, clearly a step, though only a step in the right direction. An arrangement providing the correct distribution by means of capacitance, and at the same time eliminating the difficulties shown for the device of Fig. 7 gives ideal results. The dimensions are brought within very satisfactory limits by placing between the successive disks, suitably designed and proportioned condensers. Such condensers can easily be produced to stand the required voltage and to give, in very moderate dimensions, all the capacity that is required for the purpose.

Practical Design of Condenser Type Terminal. Fig. 8 shows diagrammatically the construction of such a terminal. The values of capacitance between disks are graded so as to obtain uniform distribution of potential throughout the entire length of the terminal. The capacitances are largest near the lead sheath, the smallest capacitance being near the high-voltage end. (Actually, on account of the increased effect of capacitance to ground of the individual condensers at the points of high potential compared with the effect of their capacitance to the conductor, the condenser of minimum capacitance is slightly removed from the high-voltage end.) The concentration of stress at the edge of the disks is overcome by supplying them with lips which almost completely enclose the entire cable insulation within the terminal, the condensers being insulated from each other by a wrapping of varnished cloth. A test terminal of this type is shown in Fig. 9. To illustrate actual dimensions, as used for testing cables up to 3 in. in diameter, the individual condensers are about 3 in. inside diameter, about 7 in. outside diameter, and ½ in. to 1 in. in thickness. The group of condensers made up in this way is ordinarily enclosed in a suitable tube of insulating material and impregnated in insulating oil. With such arrangement, and with condenser stack less than 4 ft. long, many tests have been made on various sizes of cable at voltages up to 350 kv. One cable having 26/32-in. insulation was tested for over 200 hours at 300 kv.

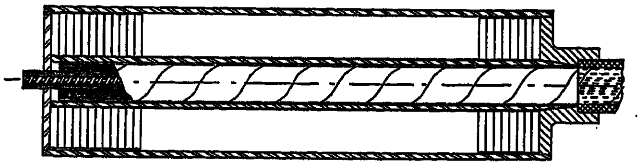
FIG. 9—PRACTICAL DESIGN TEST TERMINAL WITH DISK TYPE CONDENSERS. (DETAILS OMITTED.)

Condenser Type Joints. The same principles have been applied to joint design. Some new problems are there presented but these were satisfactorily solved and highly efficient joints were produced. However, the much lower cost of the type of construction now to be described has caused this later design to displace entirely the earlier one.

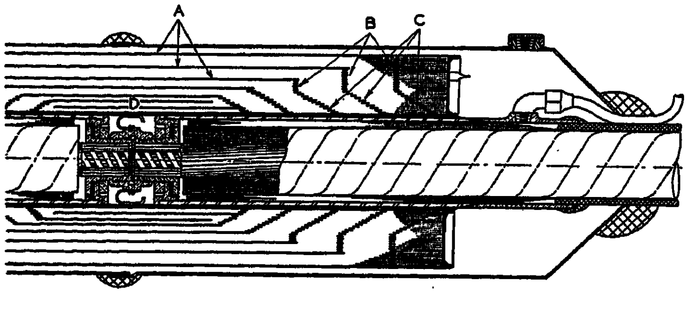

FIG. 10—CONDENSER JOINT WITH CYLINDRICAL TYPE CONDENSERS

New Form of Condenser Construction. In this design, a schematic cross-section of which is shown in Fig. 10, longitudinal distribution of voltage is likewise controlled by condensers. The condenser electrodes, however, are made up of a nest of conducting cylinders *A* of different diameters arranged coaxially with the conductor and insulated from each other by saturated paper insulation. At the ends of these cylinders are radial sections *B*, which are in effect conducting disks, terminating at their inner edge in short cones *C* by means of which electrical connection is made to various points along the exposed cable insulation, thus controlling the longitudinal stress distribution in this region. The potential of the successive cylinders is controlled so as to produce the desired longitudinal distribution by adjustment of the respective capacitances between them. Two methods of accomplishing this are used. The thickness of the paper insulation between successive cylinders is varied, or multiple layer condensers are produced by connecting alternate cylinders in parallel as shown at *D*. As the first condenser is connected to the conductor and the last condenser to the sheath the potentials of the intermediate points are determined by the series of condensers. For uniform potential distribution the capacitance required for successive condensers increases progressively from the inner part toward the outer due to the fact that the outer condensers carry not only the charging current of the inner ones but charging current from the conductor to the successive flaring end sections. For example, in joints recently manufactured for use on a 500,000-cir. mil cable with ½-in. hollow core and 26/32-in. insulation, 15 condenser steps were used, and the capacitance required for a given potential drop on the outer condenser is approximately 45 per cent greater than that required on the inner.

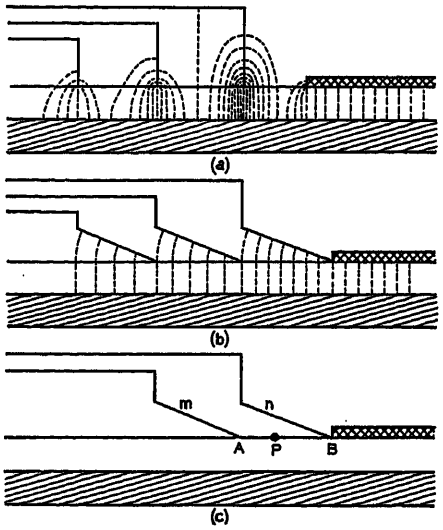

FIG. 11—EFFECT OF SLOPE OF THE CONICAL SECTION OF CONDENSER ELECTRODES ON STRESS DISTRIBUTION

It has been mentioned that the inner edge of the radial section of the condenser electrodes terminates in a short cone. The slope of the cone varies for the different condensers, becoming longer and with gentler slope as the distance from the center of the joint increases. In that portion of the joint near the end of the lead, there is a large potential difference between the condenser electrode and the conductor. If the radial section were brought down to the inner diameter of the joint and terminated without the cones, a very pronounced concentration of stress would occur, the lines of force being somewhat as shown in Fig. 11a.

It is obvious that by merely causing the inside edge of the disk to terminate in a cone, this concentration may be relieved as is evident from the stress diagram in Fig. 11b. Consider a portion of the joint insulation between the radial sections (or disks) of two adjacent condenser electrodes, *m* and *n* Fig. 11c and near their inner edges. This is seen to be under radial stress due to the potential difference between the overlying condenser electrode and the conductor, and under longitudinal stress due to the difference in potential between the condenser electrodes themselves. Consider for the moment only this longitudinal stress along the cylindrical surface of the insulation between the inner edges of these cones, *m* being the flanged section of the condenser electrode nearer to the conductor potential. If the angle of flare of *n* is very small, the potential of any point *P* on the surface between *A* and *B* and not very near to *A* will take a potential near that of *B*, with a result that the longitudinal stress will be very highly concentrated near *A*, with correspondingly low stress near *B*. It will further be seen that the potential at this point *P* is determined largely by the capacity relations to the conductor and to the overlying surface *n*.

It will also be evident that a minimum concentration of stress will occur if the distribution longitudinally between *A* and *B* is made approximately uniform, and furthermore, that by selection of proper dimensions the radial stress may be utilized to bring about this result. By the following approximate formula, the development of which is omitted on account of space limitations, it is possible to calculate the dimensions of the surface *n* which will give the desired distribution of potential along the surface between *A* and *B*.

$$r'' = r' \left(\frac{r'}{r} \right)^{\frac{v}{V - v}}$$

In this formula V is the voltage between the conductor and *n*, v the desired voltage between *P* and *n*; r the conductor radius, r' the radius at *P*, and r'' the required radius of *n* over the point *P*.

By plotting the points thus calculated for the region near the end of the lead, it will be found that the theoretical curve for the flaring surface to give equal voltage distribution deviates only a little from a straight line within the dimensions used. For the purposes of the joint it is approximated within the limits of practical construction by calculating the value of r'' for the point *A*, and using a straight line between the point on the conical surface thus determined and *B*. That is, the slope of the cone *n* is made such that the potential of the point of origin of the adjacent cone as determined by the radial field tends to be the same as that fixed by the capacity adjustment of the cylindrical condensers. This insures against concentration of radial stress at this point and provides substantially uniform distribution of longitudinal stress between the steps fixed by the condensers. The formula used is substantially correct near the ends of the joint where the radial field is high. In the region approaching the center of the joint, the error of the formula is progressively greater. In this region, however, the radial stress is very low and the importance of maintaining the correct angle is correspondingly less, so that the resultant design is completely adequate at all parts.

With all parts of the insulation of uniform resistivity, correct distribution for alternating current would also produce correct distribution for direct current. In the simplest form of construction, such homogeneity does not occur. Suitable practical means have been found, however, to provide resistance adjustment to produce this uniformity of distribution for direct current as well as for alternating current.

Design and Construction of Commercial Joints. For convenience in manufacture, in the making of practical joints, the condenser construction is not applied directly over the conductor insulation, but is made up as an independent factory built unit. Reference to Fig. 10 will show the construction clearly. There is an inner tube (called the "condenser tube") of rigid insulating material such as cellulak or micarta upon which the joint proper is wound. At the middle of this tube is inserted a short metal ring which forms the contact element between the conductor and the first condenser electrode. The insulation is made up of a continuous wrapping of 5-mil wood pulp paper, of a width equal to that of the total length of the condenser unit, and applied in one continuous length to the condenser tube which is mounted in a lathe especially equipped for this work. The cylindrical condenser electrodes are made of sheets of zinc one or two mils thick, and of suitable dimensions, which are wound in with the paper wrapping at appropriate intervals to provide the desired thickness of dielectric. The first of these plates is applied directly over the condenser tube, and makes contact with the central metal portion. The radial end sections of the condenser electrodes with their flaring terminations are formed by feeding in continuously with the paper wrapping, narrow foil tapes, ⅛ in. wide by 1 mil thick. The tapered or conical section is formed by feeding the spool carrying the metal tape along the tube longitudinally as the tape is wound in. Connection between the foils and the cylinders is made by soldering, and where the length of foil becomes excessive so that the reactance might interfere with the effective potential distribution under high-frequency transients, as in the radial portions where the insulation is quite thick, successive turns are short-circuited by metal pins passing radially through the tapes and intervening paper.

When the winding of the condenser unit is complete, the whole unit is encased in a thin sheet of corrugated copper. After preliminary drying, sheet copper end sections provided with copper tubes for saturation are soldered in place and final drying and impregnation with transformer oil is accomplished in specially constructed vacuum tanks arranged with automatically controlled electric heating and special high vacuum pumps. After the copper tubes through the end are sealed off, the condenser units are ready for test. By a very simple temporary assembly, each unit is submitted to a routine high-voltage test before shipment. The possibility of making such a test constitutes a distinct advance over previous jointing practise. The corrugations in the copper casing provide ample capacity for expansion and contraction of the oil due to any changes in temperature either in handling before installation or in service afterwards.

It will be seen that continuous oil films exist in the space between the condenser tube and the stop tube, and between the stop tube and the factory applied insulation. The longitudinal stress in the films in the portion of the joint under the condenser unit is controlled by the condenser construction. In the region near the end of the joint, control of longitudinal stress is provided by tapering down the stop tube where it is fitted into the brass sleeve, this slope being calculated by use of the same formula developed in connection with the slopes in the condenser unit. Even with the longitudinal stress taken care of, however, the large radial stress on the oil film within the stop tube would be excessive and develop failure in this region except for application of the method now to be described. This construction is very simple and now seems quite obvious but has eliminated completely this point of weakness. It consists in building up the conductor insulation inside the stop tube by use of a tube of impregnated paper, which is arranged to be slipped over the end of the cable and tightened up on the factory insulation by twisting in the proper direction. The paper is cut to give the proper taper at the end next the lead and this tapered portion is covered with metal after the paper tube is in place. The diameter to which the insulation is built up in this way may be made sufficient to reduce the stress at the outer surface to a value well below that which will produce ionization in the oil film.

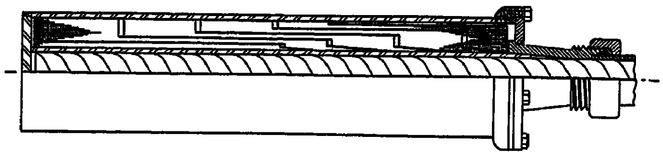

Fig. 12—Simplified Assembly of Test Terminal with Cylindrical Type Condensers

Where the stop feature is not to be used, the stop tubes are omitted and the exposed cable insulation is built up to the desired diameter by the use of a similar tube of impregnated paper. This makes it possible to use a condenser tube large enough to slip back over the lead with ample clearance, and insures against discharges over the surface of the factory insulation.

Cylindrical Type Condenser Terminals. The same general features of condenser design have been applied to high-voltage terminals and have proved equally satisfactory. Fig. 12 shows the cross-section of a test terminal of this type. The use of the impregnated paper tube has also been applied to this and to other types of terminal with gratifying results.

Longitudinal Strength of Oil Films. By this construction it has been possible to obtain substantially uniform longitudinal distribution of stresses and the limiting feature in design has become the actual strength of thin oil films longitudinally and of the impregnated paper insulation in a direction parallel to its laminations. In earlier joints, the high local concentrations of stresses were not easily determined and were usually not known, hence practical methods of reducing these maximum stresses or of introducing constructions giving higher dielectric strength at the points where they occurred were of more importance than information as to the stress which could be sustained by the film if the potential were uniformly distributed. Consequently, very little previous work has been done in determining specific values of longitudinal strength, and so far as we know, there are no published data on the subject. We have found that the longitudinal strength is of the order of 10 per cent of the radial strength. While, in general, factors tending to affect the strength in one direction have a similar effect on the strength in the other, the degree to which they affect these two values is found in some cases to vary enormously. For example, both are affected by the degree of saturation, but the effect on the longitudinal strength is very much more pronounced. On the other hand, the element of time has a very important effect on radial strength while its effect on longitudinal strength is much smaller. As a result, tests involving both radial and longitudinal stresses are more likely to produce longitudinal failure when made at very high voltages for short time and radial failures when made as long-time tests at lower voltages.

A large amount of experimental data has been obtained concerning the longitudinal breakdown strength of oil films similar to those in the cylindrical condenser joints. Tests were made on some 350 specimens constructed by winding strips of 1-mil foil between the layers of a paper tube, using spacings of from $\frac{3}{8}$ in. to $\frac{3}{4}$ in., the samples being impregnated with oil under vacuum and tested under pressures ranging from atmospheric to 55 lb. per sq. in. absolute. No attempt was made to eliminate "edge effect," the intention being to reproduce substantially the conditions in the condenser units. For the conditions of the tests, the results obtained have enabled us to draw the following conclusions:

a. Longitudinal breakdown strength of such an oil film one mil thick with one inch separation of electrodes and tested under 20 lb. per sq. in. gage pressure —40 to 60 kv.

b. No indication of reduction of strength with increase of time of application was found within the limit of the times used in these tests. (1 second to 30 minutes.)

c. Longitudinal breakdown under the conditions of test varies as about the square root of the distance between the electrodes.

d. The effect of pressure is to increase the breakdown strength as something like the eighth root of the absolute pressure.

Test Results on Joints. Typical results of tests on complete joints may be of interest. On the earlier joints having a total of 14 in. longitudinal creepage distance, tests were obtained up to 300 kv. for approximately 8 hours without failure. Further tests on other joints with creepage distances down to 8 in. have given results which are about proportional to the one just cited.

CONCLUSION

In earlier designs of joints and terminals for very high operating voltage, the difficulty with concentration of stress increases with increased voltage, so that a small increase in voltage requirements necessitates an entirely disproportionate increase in joint and terminal dimensions. As a result, a rather definite limit was established, beyond which further increase in voltage was impracticable. Since the condenser construction provides complete control over the potential distribution, any increase in voltage may be taken care of by a proportional increase in creepage distance and in the number of condenser steps. Consequently, by a simple adjustment of dimensions, the advantages already derived from the use of joints and terminals of this type on the highest voltages now in use become equally available for any operating voltage for which cables may later be built.

These developments have made possible the realization of a unified oil-filled cable system which involves a minimum of complication and which, in the higher-voltage range, has a decided cost advantage over solid type cables. This system not only fully realizes the outstanding advantages inherent in the oil-filled principle, but incorporates additional valuable features. Thus, it is possible to install the cable nearly as readily as solid type cables for lower voltages. The system provides for efficient sectionalizing of the oil feed and for prompt detection of oil leaks or abnormal pressures. As a result, the freedom from electrical failure which is characteristic of oil-filled cables may be expected to be matched by freedom from service failures due to most of those external causes which result in failures on the present solid type system.

So extremely rapid has been the development which has taken place in this field in methods of manufacture and in the improvement in the technique of handling and of installation, that problems which only a comparatively short time ago seemed to be extremely difficult have become of minor importance. An increasing volume of information gives assurance that oil-filled cable will fulfil all theoretical expectations, and as a result, it has opened up entirely new fields of usefulness for insulated cables.

Grateful acknowledgment is made to the many associates of the authors who have contributed largely to the development here described and to the utility engineers who have cooperated in obtaining data on performance of oil-filled cables and accessories in actual operation.

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Discussion

For discussion of this paper see page 1447.

Residual Air and Moisture in Impregnated Paper Insulation—III

BY J. B. WHITEHEAD*
Fellow, A. I. E. E.

and

F. HAMBURGER, Jr.†
Associate, A. I. E. E.

INTRODUCTION

IN an earlier paper[1] we have described a series of studies of the influence of residual air and moisture on the properties of impregnated paper insulation. The power-factor voltage characteristics of impregnated paper, as used in high-voltage cables, are well known. A sharp rise in power factor with increase of voltage has been accepted as an indication of poor quality and generally as indicating large amounts of entrapped air or gas. One of the striking results of our studies has been the relatively small effect of residual air upon the shape of the power-factor voltage curves. The shape of these curves was not appreciably affected in the range of evacuation pressure from one to ten centimeters of Hg., absolute pressure and furthermore the curves were perfectly flat up to 300 volts per mil and 50 deg. cent. Only at impregnation pressures above 25 cm. Hg. did the typical rising power-factor voltage curve become evident. Visual examination always showed dryness and air in samples having rising power-factor voltage curves while evidence of excellent thorough impregnation was associated with samples having flat power-factor voltage characteristics.

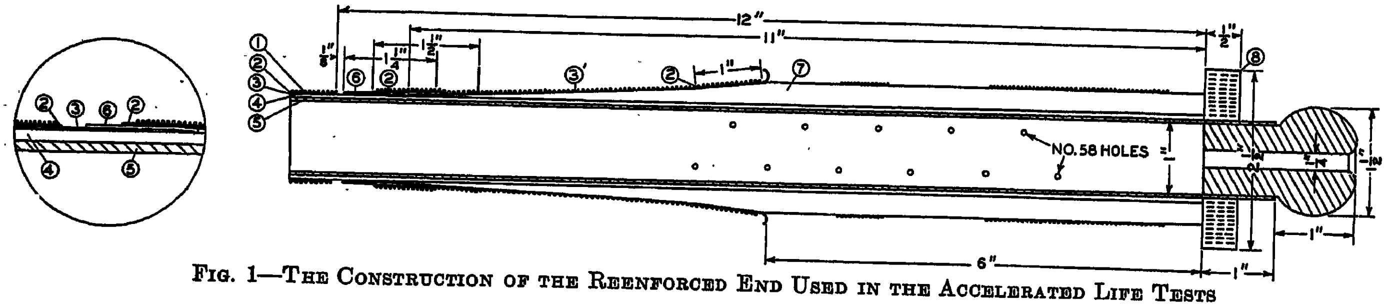

FIG. 1—THE CONSTRUCTION OF THE REENFORCED END USED IN THE ACCELERATED LIFE TESTS

THICKNESSES

1. Linen thread. 50 turns per in.
2. Lead electrode 1/64 in.
3. Foil extension of electrode 4 mils
4. Paper tape insulation 65 mils
5. Brass tube 1/32 in.
6. Paper insulation 8 mils
7. Paper end reinforcement 0.31 in. max.
8. Bakelite ring

In this paper we present the results of further study on the still open question of the influence of residual air upon the life of the finished insulation. Here, as before, we use the value of the pressure of evacuation and impregnation as a measure of the amount of residual air. As in the foregoing studies the present work has also brought out much interesting information on other phases of impregnated paper, notably in the suggestion of a possible correlation between initial changes in power factor and subsequent life.

ACCELERATED LIFE TESTS

Description of Specimens. The sample used for the accelerated life tests was much the same as that described in our earlier paper. Several modifications were necessary, however, due to the importance of strengthening the ends of the specimens to enable them to withstand the high voltages required for the accelerated life tests. The early tests resulted mostly in flash-overs and punctures of the end of the sample. In order to obtain a true test it is important that the breakdown should occur in a section of the sample in which the electric field is uniform, or in other words, under the test electrode. In the final results this condition has been met, although a tendency to breakdown towards the ends is avoided only with the greatest care in construction.

Each sample consisted of a brass tube one inch in diameter and four feet long. Each tube was cleaned and polished and drilled at each end with thirty-six No. 58 holes spaced uniformly in the region from 3 to 8 in. from each end. These holes were necessary in order to insure complete impregnation of the sample at the ends, where the insulation wall was much thicker. Each tube then received a wrapping of fifteen layers of 1-in. wide, 0.0043-in. thick, manila paper. The paper was fed on spirally in the usual manner, in each layer the successive turns lapped slightly, the lap varying from 1/32 in. to a close butt contact. The laps in successive layers were displaced successively by approximately ¼ in. The insulation wall averaged 65 mils in thickness.

Several different methods of building up the ends were tried before a satisfactory construction was obtained. Various combinations of reenforcing insulation and metal bells were tried. One of these methods met with considerable success but the most satisfactory end construction employed was suggested by R. W. Atkinson. A cross-section of this method is shown in Fig. 1. The end is built up of some 70 turns of kraft paper so cut before applying that when put in place a gentle slope resulted. A lead foil covering of this slope formed the guard electrode of the specimen. The slope was determined by calculation so as to give a uniform longitudinal stress, of a predetermined safe value, along the end of the sample. The guard laps over and is insulated from the end of the test electrode. At the outer edge the lead is turned back and smoothed to avoid sharp edges. This end has been very satisfactory and normally shows no signs of stress. This is true even in cases where a voltage of 50 kv. (800 volts per mil on the insulation wall) has been applied for as long as 180 hours.

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*Dean, School of Engineering, Johns Hopkins University, Baltimore, Maryland.

†Graduate Student, Johns Hopkins University, Baltimore, Md.

1. For references see Bibliography.

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Drying, Evacuating and Impregnating. The equipment used for drying, evacuating and impregnating has already been described in the paper referred to above which also gives details of the Schering bridge used for power-factor measurements. One new piece of equipment has been added during the present investigation. This is a chamber into which compound can be admitted under vacuum for the removal of air and other gases. The compound is piped directly from this chamber to the impregnating tank and thus is never in the presence of air after it has once been treated under vacuum.

In view of the importance of residual moisture all the paper samples were first dried to the same standard condition before impregnation. This standard condition was determined by the value of the d-c. conductivity measured at 1,500 volts as described in the first paper. Two methods were used to obtain this standard dry condition. The specimens were either dried in air for 72 hours, or were subjected to a vacuum of ½ mm. Hg. for 48 hours. The temperature for both methods was 105 deg. cent. Check measurements showed that both methods resulted in samples having similar characteristics.

The specimens, having reached the dry state, were evacuated to the various pressures to be studied. For the samples dried in the open this evacuation of 24 hours took place immediately after the air drying period. For the vacuum dried samples a 24-hour period in dry air at atmospheric pressure and 105 deg. cent. was inserted between the drying and evacuating periods in order to offset the effect, on the amount of residual air, of the low vacuum of the vacuum drying treatment.

Following the evacuation treatment at 105 deg. cent. and at the particular pressure being studied, the temperature of the samples was reduced to 60 deg. cent. while the evacuation pressure was maintained. When a constant temperature of 60 deg. cent. was reached the impregnation was started. The samples were impregnated by slowly admitting compound and holding the pressure constant in the impregnating chamber. This was accomplished by regulating properly the opening of the inlet valve and the speed of the vacuum pump. The compound was always evacuated at ½ mm. and 60 deg. cent. before being used for impregnation. After the necessary amount of compound had been admitted to the impregnating chamber the pressure and temperature were held for two hours at the same values used during the impregnation. Following this two-hour interval the pressure in the impregnating chamber was raised to atmospheric by the admission of nitrogen. Direct current measurements of conductivity were then made, after which the samples were allowed to cool to room temperature.

The oil treating equipment consisted of an open reservoir into which the compound was emptied from the containers in which it was shipped. In this reservoir the compound was heated to 60 deg. cent. It was then slowly admitted into the treating chamber which had previously been evacuated to a pressure of ½ mm. Hg. During the admission of the compound this pressure was maintained. The oil passed into the treating chamber through a spray nozzle and was sprayed on the apex of a metal cone. Thus the oil was spread out in a thin layer to facilitate the removal of air and gas. From the top cone the oil dripped on to two other cones and then into the bottom of the chamber where it was stored until needed for impregnation.

After the specimens had been allowed to cool to room temperature in the impregnating chamber they were transferred to the high-voltage test box where they were immersed in compound for the tests. In some cases all three of the samples were transferred at the same time, in other cases they were transferred singly and while one sample of the set was under life test those remaining were kept in the impregnating chamber under compound in an atmosphere of nitrogen.

TEST PROCEDURE

Life Tests. For the accelerated life tests it was found desirable to use a value of stress that would give a reasonably long life, say twelve hours, for the poorest specimens and a short enough life for the best specimens so that the testing would not stretch out over too long a period. It was found early that the range of quality of the samples being tested was entirely too wide to permit the use of one given voltage stress for all the tests. After feeling our way in the preliminary experiments the following test procedure, known as "standard test procedure *A*," was adopted:

400 volts per mil for 22 hours
500 volts per mil for 22 hours
600 volts per mil for 112 hours
700 volts per mil to breakdown
Power factor measured two hours after each change of voltage, and then every four hours.

This procedure was used throughout the first group of accelerated life tests. Following this first group a second series of samples was run through in which a newer type of compound was used for impregnation. This new compound resulted in samples having a considerably longer life than those of the first group. Consequently test procedure A was found to be too slow and a more rapid procedure was developed. This is known as "standard test procedure B," and is as follows:

400 volts per mil for 1 hour
500 volts per mil for 1 hour
600 volts per mil for 10 hours
650 volts per mil for 10 hours
700 volts per mil for 37 hours
750 volts per mil for 40 hours
800 volts per mil to breakdown
Power factor—first measurement at the start and then once at each change of voltage.

The life tests were all conducted at a constant temperature, 40 deg. cent. This value was decided upon as it was well within the operating range of insulation of this type and was sufficiently above the range of ambient values to permit good temperature control. The temperature was maintained, in most cases, to within plus or minus ½ deg. cent. In several tests of very poor specimens the energy dissipated as dielectric loss was so large that it was impossible to hold the temperature down to 40 deg. cent. In one such case the temperature rose to 51 deg. cent. before breakdown. This condition was only encountered in two instances.

The life tests on a group of three specimens were made both singly and three in parallel. Some difficulty was experienced in the use of the parallel connection. This was first noticed by a marked absence of uniformity in the life of the three specimens of one group. The third specimen invariably showed a much longer life than the other two. This was at variance with the results of the tests on single specimens which were very satisfactory from the standpoint of uniformity. There was evidence that the parallel arrangement facilitated the occurrence of oscillations whenever an initial local failure started. These oscillations resulted in the liberation of excessive energy at this point of initial failure, with greatly accelerated approach to breakdown. The first attempt at correction was to insert resistors, of approximately 8,000 ohms each, in the high-tension lead between each outer specimen and the middle one. This improved conditions somewhat but was not entirely satisfactory. A resistance of the same value (8,000 ohms) was then inserted in the high-tension lead in series with each specimen. This connection proved to be fairly satisfactory and enabled us to test some of the specimens in parallel. In view, however, of a continued uncertainty as to the presence of this type of disturbance, the majority of the samples were tested singly.

Power-Factor Measurements. As a preliminary check of the character of the impregnated specimens, power-factor measurements over the voltage range from 60 to 300 volts per mil and at two temperatures, room and 40 deg. cent., were made on most of the specimens before starting the life test. In some cases the power-factor voltage relations were also studied at 60 and 80 deg. cent.

The life test of each specimen, tested by procedure A, was interrupted for about six minutes at intervals, usually four hours, in order to measure the power factor. This was only done for those specimens which were tested singly. These measurements permitted us to study the variations of power factor during the life of the specimens. For the samples tested by procedure B the power-factor measurements were taken only at each change of voltage. These measurements brought out a number of interesting points which will be discussed later.

Visual Examination. All the specimens tested to destruction were stripped and examined and the condition of the insulation noted. In the early stages of the work the points of breakdown showed considerable evidence of disruptive discharge. The burned areas were large and badly torn. Subsequently the breakdowns took the form of clean punctures of the insulation. These punctures were generally cone shaped holes about 3/16 in. in diameter at the sheath and tapering to a point at the conductor. The area around this type of break was clean and showed the same visual character as unstressed insulation except in some few cases in which the insulation in the vicinity of the break was very dry and contained only a very meager amount of compound.

The disruptive type of breakdown we attribute to oscillations at the instant of failure. Careful grounding and shielding of all circuits eliminated this type of failure. Similar disruptive breakdowns occurred in the parallel test connection before the insertion of damping resistors.

The specimens that were short lived showed, upon examination, evidence of large quantities of entrapped air or gas and incomplete impregnation as was indicated by the dryness of the paper tape. The best specimens were all well impregnated, thoroughly saturated with compound and free of any signs of voids or air spaces. Intermediate specimens were in general well saturated and free of air or gas. These specimens would occasionally show traces of gas at the tape edges.

RESULTS

Voltage-Time Relations. In any study of the life of impregnated paper insulation it is obvious that an accelerated life test is necessary. Furthermore, in order to investigate insulation having a wide range of quality a step test is essential. This immediately raises the question of a basis of comparison as related to the various voltages of the step test.

Very little information is to be found in the literature concerning the voltage-time relations of impregnated paper insulation. In general two types of relationships have been proposed. The first is based on a voltage-time curve which becomes asymptotic to a line parallel to the time axis and gives a law stating that the life varies inversely as some power of the voltage in excess of the value of the asymptote. The second states that the life varies inversely as some power of the voltage.

F. W. Peek, Jr.[2] suggested a law for the first type of relationship. He found that for impregnated paper tested for breakdown in the range from a fraction of a second to sixty seconds the curve fitted the expression

$$G = G_s\left(1 + \frac{a}{\sqrt[n]{t}}\right)$$

where G is the breakdown gradient for a time t and G_s is the gradient which the insulation will stand for an infinite time without failure. The constant a depends on the type of insulation, the temperature and other factors. Peek found that for his experimental results the value for n was four.

J. Delon[3] investigated this relation further and pointed out that the value of n is not a constant when t varies over a wide range. He found in his experimental work that n increased from four to eight when t changed between the limits of one to two thousand hours.

W. Schmidt[4] has given an interesting discussion of the voltage-time relationship of this type. He proposes a method for the determination of the quality of a given sample of insulation on the basis of the instantaneous breakdown strength and the so-called limiting voltage. He takes the value of n as two and criticizes the use in this country of values as high as seven and eight.

From their experiments on three-conductor cable impregnated with heavy oil, D. W. Roper and H. Halperin[5] find that the second type of relationship agrees with their data. They state that "the breakdown voltage varies inversely as the seventh root of the time." F. W. Farmer[6] and F. M. Clark[7] independently check this seventh root relationship. Clark calls attention to the fact that the type of insulation and the temperature as well may vary the slope of the voltage-time curve.

The first type of relationship appears to be more logical but the second seems to be in favor among insulation engineers. It is apparently, based on the average results of extended periods of observations of commercial breakdown tests, the power of the voltage varying from the fourth up to as high as the nineteenth. The power is assumed to depend upon the duration of the test as well as the quality of the insulation. It is obvious that there is little exact knowledge of the subject and that no general law exists. It seems to be agreed, however, that as a method of comparison the simple inverse power relation is roughly reliable, with a considerable range of the power of the voltage. Our tests have all been of comparatively short duration and our insulation of high quality. Discussion with others working in the same field led us to adopt the eighth power law as a basis for comparison in our tests. All our specimens, therefore, were reduced to "hours life at 400 volts per mil" on this basis.

Our results show that this law is only a mode of comparison and in the longer lived specimens it leads to ridiculous results. For example, considering 100 volts per mil as an average operating stress and taking 6,000 hours at 400 volts per mil as the average life of a good quality sample, calculation on the basis of the eighth power law gives an equivalent life at 100 volts per mil of over 50,000 years! Systematic studies of the law of life, as related to the length of accelerated life tests, are badly needed.

As a matter of interest the first type of voltage-time relationship has also been considered in studying our results. This is the law suggested by Peek, Delon, and Schmidt and it assumes that there is some voltage greater than zero for which the insulation life would be infinite. The life of the insulation, then, is inversely proportional to some power of the excess of voltage over this base voltage. The present tests indicate that for the type of sample and compound used a base voltage of 400 volts per mil and the fourth power of the excess of voltage over that base gives reasonable results. The lives of several specimens have been recomputed on this basis and compared with the same lives calculated by the eighth power law. The relative differences between specimens is practically unchanged and the second method of calculation modifies the results not at all, except as to the numerical values of the estimated life.

Life-Pressure Relations. In all, over 135 samples have been built and tested to destruction. Of these 60 samples were used in the development of a reliable method of test and the remainder have been used in the actual results. The results are shown in Figs. 2 and 3. Each point is the average of from five to nine separate tests.

The curve marked A in Fig. 2 shows the variation of life with the pressure of impregnation for samples impregnated with a compound designated as A. The points on the curve are average points and represent all samples except those in which the test was not truly representative of the insulation strength, such as tests in which there were end failures or other troubles. One is struck, upon looking at the curve, by the small difference in life obtained by reducing the air pressure of impregnation from 2.5 cm. to 2 mm. Hg. This is due to the difficulty of obtaining reliable points at these low pressures. It was very difficult to obtain failures in sections of the insulation wall in which the electrostatic field was unquestionably uniform. It seemed desirable therefore to investigate further this particular pressure range and to modify the specimen construction so as to improve the reliability of the results.

The original supply of compound A having run out, it was necessary to obtain a new one. As it was impossible to obtain a duplication of the first supply another compound had to be used. This question will be discussed further in another section of the paper. This second supply of compound has been designated as compound B and the results of an extensive series of observations using it are plotted in the curve marked B of Fig. 2. The results here are more reliable than those of the curve A, within the same pressure range.

We have shown for curve *B* a much wider difference in life than in the corresponding section of the life curve *A*. The curve *B* shows an increase of 50 per cent in life for a decrease in pressure from 2.5 cm. to 2 mm. The data show definitely an increase in life in this pressure range of 10 per cent and indicate, we believe, the increase of 50 per cent shown on the curve.

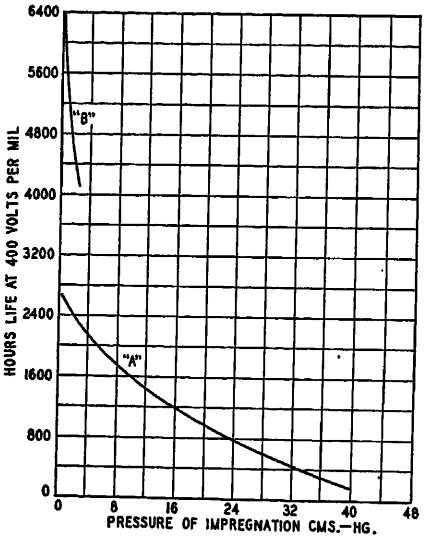

FIG. 2—RELATION BETWEEN THE PRESSURE OF IMPREGNATION AND THE LIFE OF IMPREGNATED PAPER INSULATION

Compounds *A* and *B*

The scattering of the points obtained at the 2.5 cm. and the 2 mm. pressures is shown in Table I. The average values used in plotting the curves have been based on a critical analysis of all the results. Careful study of the test and the examination of each sample led to the selection of those used in computing the average. For example, the first column of Table I shows a range of life from 232 to 3,850 hours. Out of a total of twelve tests five were rejected due to the proximity of the failure to the sheath cut between central electrode and guard.

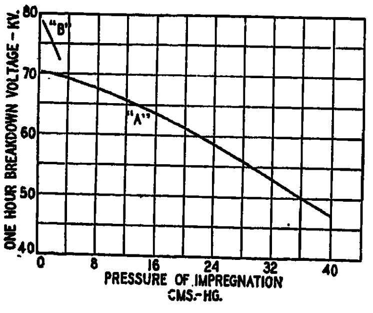

FIG. 3—RELATION BETWEEN THE PRESSURE OF IMPREGNATION AND THE ONE-HOUR BREAKDOWN VOLTAGE OF IMPREGNATED PAPER INSULATION

TABLE I

Impregnating pressures	2 Mm.		2.5 Cm.	
Compound	A	B	A	B
Hours life at 400 volts per mil..	1,483	12,290*	2,262*	4,618*
	3,850*	4,100*	896	3,809*
	2,102*	4,213*	668	4,049*
	3,025*	6,189*	2,332*	4,308*
	474	11,614*	251	4,221*
	2,365*	863	2,102*	
	1,345	372	2,442*	
	2,377*	4,141*	1,909*	
	420	4,383*	3,156*	
	232	4,035*		
	3,059			
	2,091			
Average	2,695	6,370	2,367	4,141

*Indicates specimens used in computing average.

The results when examined in detail offer an explanation of the difficulty in obtaining uniform results in the tests in this low-pressure range. When the impregnation pressure is 2.5 cm., or lower, a region of pressure is reached in which the normal variations in the structure of the sample become so important that they may overshadow the effect of the reduction in air pressure. This is true despite the most extreme care in the manufacture and preparation to secure uniformity of the samples. One of the most important variations has been found to be the tightness of the assembled structure.

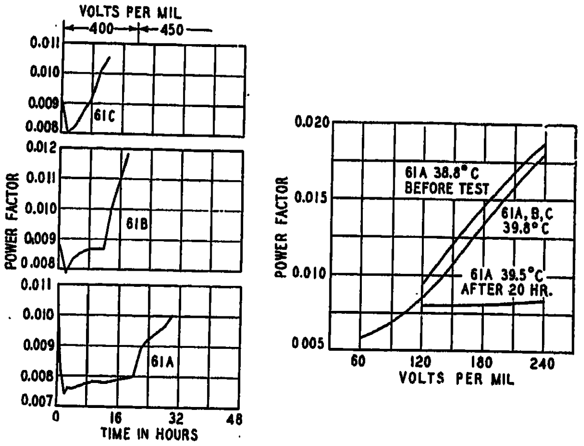

FIG. 4—POWER-FACTOR-VOLTAGE CHARACTERISTICS AND THE VARIATION OF POWER FACTOR DURING THE LIFE TEST OF SET 61

Impregnated at 40 cm. Hg.

Variation of Power Factor During Life Tests. As already stated, power-factor measurements were made on all specimens before the start of the life tests. The power factor was also measured at 180 volts per mil at intervals during the life of the specimen. These observations brought out several interesting results. The characteristics of samples impregnated with compound *A* will be discussed first.

Fig. 4 shows the power-factor voltage curves for specimens of set No. 61, which were air dried to our standard dry condition and then evacuated and impregnated at 40 cm. Hg. The pressure on these specimens was never reduced below 40 cm. so that this set may be considered good from the standpoint of moisture and poor from the point of entrapped air. The power-factor voltage curves are sharply rising as is characteristic of this type of specimen. The life test of 61-A has the immediate effect of bringing the power-factor curve down to an approximately horizontal position after 20 hours. During the test on the *A* specimen, the *B*, and *C* specimens are under compound at about 38 deg. cent., which seems to improve their power factor somewhat, although the curves of power factor are still sharply ascending. This apparent improvement has been noted before and shown to be only temporary (see earlier paper). However, under life test these curves flatten out as did the curve of specimen 61-A. While this indicates an improvement in the ionization factor of the insulation, there is evidently a corresponding deterioration as shown by the increase of power factor with time, also indicated in Fig. 4.

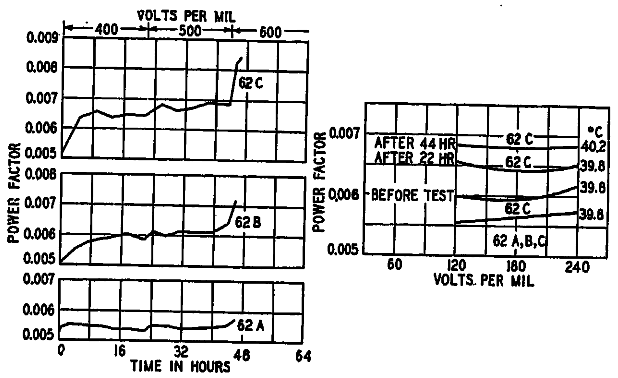

FIG. 5—POWER-FACTOR-VOLTAGE CHARACTERISTICS AND THE VARIATION OF POWER FACTOR DURING THE LIFE TEST OF SET 62

Impregnated 15 cm. Hg.

Our experiments show that this initial clean-up of the insulation becomes less noticeable as the amount of residual air in the insulation is decreased. This can readily be seen by referring to Fig. 5 for set No. 62. Here, since the pressure of impregnation was relatively high, 15 cm., the power-factor voltage curves are not as flat as those observed for our best specimens, but have a slightly rising characteristic. The power-factor time curves, Fig. 5, show no evidence of a decrease of power factor upon the application of voltage, but rather tend to an ever increasing power factor as the time of stressing lengthens. Furthermore, power-factor voltage measurements after 22 and 44 hours under stress show curves which lie successively higher.

Specimens impregnated at low pressure and dried to our standard condition show the typical flat power-factor voltage curves discussed in our earlier papers. In addition the power-factor time curves taken during the life of the insulation are of interest. Curves of this general type are shown in Fig. 6 for set No. 65. As a rule a slight rise in power factor is noted during the first two hours following the application of voltage after which the power factor remains constant at this increased value for the next 20 hours. At this point the voltage stress is, according to the standard procedure *A*, stepped up to 500 volts per mil. This increase in stress is also accompanied by an increase in power factor, followed by another 20-hour period without further change. The voltage increase to 600 volts per mil, which then takes place, is accompanied by another increase in power factor. The power factor then remains practically constant up to the breakdown. The large increase of power factor which would be expected to precede the breakdown takes place relatively rapidly, generally within four hours. This point is brought out in Fig. 6 for specimen 65-B. It is interesting to note that the power factor gives no indication of approaching breakdown except within this very short interval before failure. This seems to be strictly a characteristic of good specimens, *i. e.*, specimens impregnated at low pressure, while to the contrary, specimens impregnated at high pressure and known to contain air, show, as a rule, an ever increasing value of power factor from the start of the application of voltage to the point of breakdown. This rise follows the more rapid decrease in power factor which occurs, in these specimens, immediately upon the application of voltage, as noted above.

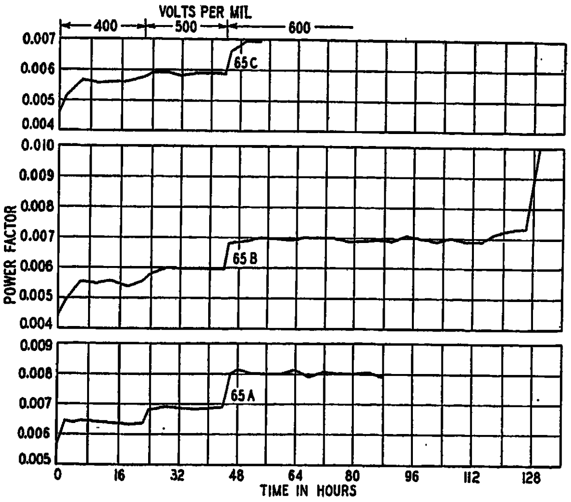

FIG. 6—VARIATION OF POWER FACTOR DURING THE LIFE TEST OF SET 65

Impregnated at 3 mm. Hg., compound *A*

In the studies made with the compound *B* the power-factor time curves have a somewhat different character. (Fig .7.) Fewer power-factor measurements were made during the life tests of this group of samples so that only the general tendency of the power-factor time curves is given. For this type of specimen we find also the initial rise of power factor found with the good samples of group *A*, but following this initial rise the power factor decreases steadily throughout the life of the sample. The power factor doubtless rises just before breakdown, but it happened that no measurements were made during the short period before failure so that no rises are shown at the ends of the power-factor time curves for this group of samples.

Predetermination of Insulation Life. All through the life test work the data were carefully studied in an effort to find some "yardstick" by which the life might be measured. Attention has been called to the fact that in all the life tests in which the power-factor voltage curves showed a flat or fairly flat characteristic the application of voltage, for the first step of the life test, was accompanied by an increase of power factor as was noticed in Fig. 6. This rise in power factor has been carefully computed, for all the samples impregnated with compound *A*, and compared with the life of the insulation.

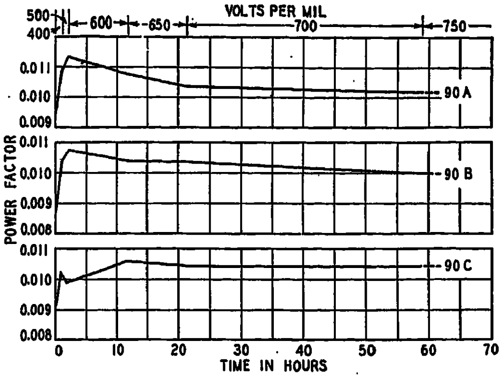

FIG. 7—VARIATION OF POWER FACTOR DURING THE LIFE TEST OF SET 90

Impregnated at 2 mm. Hg., compound *B*

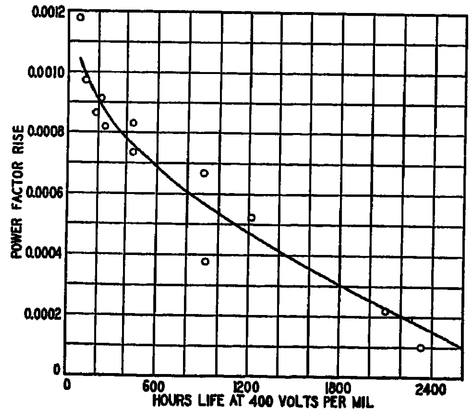

FIG. 8—RELATION BETWEEN INITIAL POWER-FACTOR RISE AND THE LIFE OF IMPREGNATED PAPER INSULATION

Compound *A*, specimens tested in parallel

The results of this comparison are shown in Figs. 8 and 9. There is apparently a definite relation between this initial power-factor rise and the life of the insulation. Further study of the question is advisable. The relationship between power-factor rise and life might well be different for different kinds and types of insulation. It is quite possible, too, that under other conditions of test than those used here the effect might not be so evident. However, it appears to be sufficiently striking to warrant calling to the attention of the workers in this field. A similar analysis was not possible for compound *B*, owing to the small number of measurements of power factor.

VARIATIONS IN CABLE PAPER

During the course of the work we have had occasion to handle three separate lots of manila paper. These three supplies we will call Nos. 1, 2, and 3. The original supply was No. 1 and the two subsequent supplies Nos. 2 and 3, respectively. All three supplies were ordered under the same specifications. In the life test work reported in this paper only paper No. 3 was used. Papers Nos. 1 and 2 were used in some preliminary work and several results of interest were obtained.

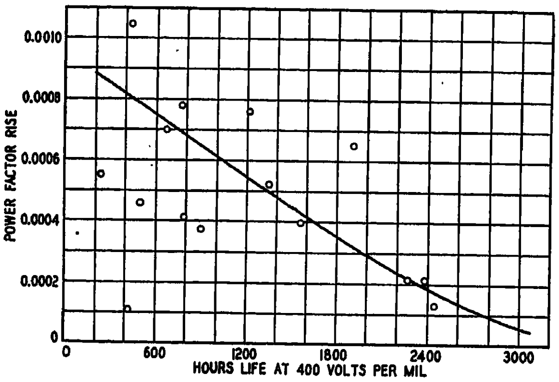

FIG. 9—RELATION BETWEEN INITIAL POWER-FACTOR RISE AND THE LIFE OF IMPREGNATED PAPER INSULATION

Compound *A*, specimens tested singly

In the earlier paper[1] we have described in detail our methods of drying and the use of the d-c. conductivity as a criterion of dryness. The work described in these earlier reports was all carried out with paper No. 1. The dry condition was indicated by a galvanometer deflection of 3.00 cm., twenty minutes after the application of 1,500 volts direct current, representing a resistivity of 6.02×10^{14} ohms per cm.[3]. This dry condition was normally reached after drying for 72 hours at 105 deg. cent. in the open air or it was invariably obtained following a 48-hour treatment at a pressure of 2 mm. Hg. and 105 deg. cent.

An attempt to dry paper No. 2 to the foregoing standard condition met with failure although paper No. 2 was supposed to be the same as paper No. 1. In order to check the difference in these two papers two identical samples were made up, one with paper No. 1 (50E) and one with paper No. 2 (50D). These two specimens were placed side by side in the drying chamber and subjected to the same drying process. The results are given in Table II.

TABLE II

Specimen	Time in hours at 105 deg. cent.	Galv. defl. cm. 20 min. at 1,500 volts
50 D	24	77.0
Paper No. 2	48	42.5
	72	30.5
50 E	24	10.1
Paper No. 1	48	8.0
	72	7.15

This test showed conclusively that there was some inherent difference in the two papers. The matter was taken up with the manufacturer who informed us that the porosity of these two papers was somewhat different, No. 1 having a porosity corresponding to 322 seconds as compared to 100 seconds for paper No. 2. The manufacturer offered to supply another lot of paper having the same characteristics as No. 1. A group of specimens made up with this shipment of paper, No. 3, when dried, showed properties equivalent to paper No. 1. Table No. III shows the comparative drying data for the three papers.

TABLE III—DRYING DATA FOR THREE SHIPMENTS OF CABLE PAPER

Paper	Time to reach	Conductivity of cm.	Remarks
No. 1	In air 72 hr	3 cm.	Standard conductivity 3 cm.
	Vacuum 24 hr,	3 cm.	Drying temp. 105 deg. cent.
No. 2	In air 5 weeks	Could not get down to 3 cm.	
	24 hr. vacuum	15.3—20.0	Could not get down to 3 cm. in 120 hr.
	48 " "	8.8—11.5	
	72 " "	6.4— 8.5	
	96 " "	4.8— 6.4	
	120 " "	4.5— 5.9	
No. 3	24 hr. vacuum	1.25—2.00	Equivalent to the original paper Deflection lower due to slightly thicker insulation wall

A group of specimens, set 51, made up with paper No. 2, was vacuum dried and impregnated at 2-mm. pressure. The results obtained are shown in Figs. 10, 11, and 12. Fig. 10 gives a comparison of the power-factor voltage curves of this set and those of set 4 which was made under similar conditions but using paper No. 1. The differences are very striking. The power factor of paper No. 2 rises with increasing voltage at all temperatures in contrast to the flat and decreasing power factor with increase of voltage observed for paper No. 1. The values of power factor are also higher, being almost four times as large at 60 deg. cent. Fig. 11 shows the correlation between power factor and absorption which we have discussed in our earlier papers and also brings out most markedly the difference in the two papers. Fig. 12 shows the charge and discharge curves for these two sets. Fig. 13 for set 55 made up with paper No. 3 shows that for this paper the power-factor voltage curves are in line with those of paper No. 1. The only difference noticed between papers Nos. 1 and 3 was that paper No. 3 was about 0.0005-in. thicker than paper No. 1.

Summarizing, paper No. 2 was much more difficult to dry than paper No. 1 and even after a prolonged period of treatment failed to reach a conductivity as low as the normal value for paper No. 1. Impregnated insulation made up using paper No. 2 showed values of power factor higher than those found for paper No. 1 and the increase of power factor with temperature was much more rapid. At 60 deg. cent., for example, numerical values four times as large as those for paper No. 1 were encountered. At the higher temperatures impregnated insulation using paper No. 1 always showed power-

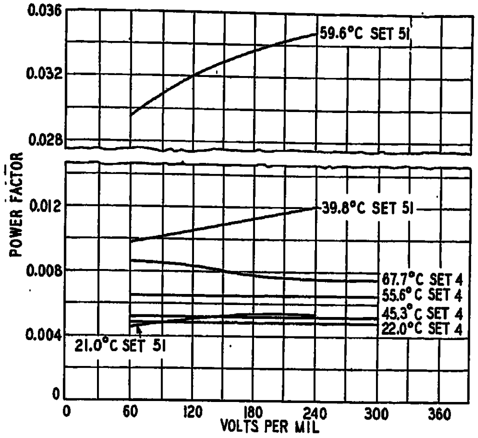

Fig. 10—Relation Between Power Factor and Voltage for Two Different Cable Papers

Set 4—paper No. 1
Set 51—paper No. 2

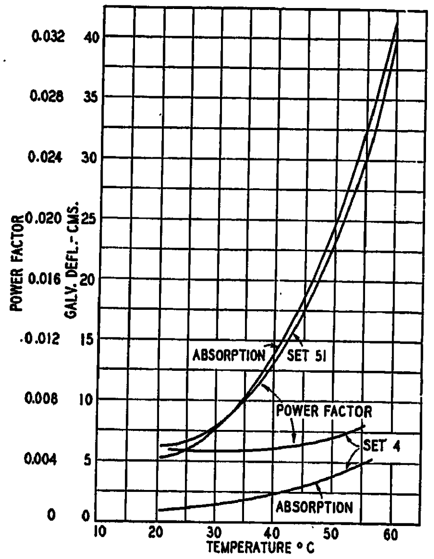

Fig. 11—Relation Between Absorption and Temperature and Power Factor and Temperature for Two Different Cable Papers

Set 4—paper No. 1
Set 51—paper No. 2

factor voltage curves decreasing with increasing voltage, paper No. 2 shows rising power-factor voltage curves in the same high temperature region. We attribute the differences in the performance of papers 1 and 2 to inherent differences in their composition.

VARIATIONS IN COMPOUND

Compound *A* was used over a period of eight months. During this time it was stored in the sealed five-gallon tins in which it was received. After using it for tests throughout a six-month period a marked decrease of life was observed in an attempt to check an earlier run. Investigation showed quite definitely that the compound had deteriorated. Specimens manufactured under conditions which earlier gave lives of over 2,000 hours would fail in less than half that time after the compound had been standing several months before using. Study of the data brought out the facts shown in Fig. 14. The d-c. conductivity and the increase in power factor from room temperature to 40 deg. cent. increased steadily with the age of the compound. We attribute this deterioration to the presence of air in the compound, although it was evident that a considerable degree of vacuum existed in the sealed container.

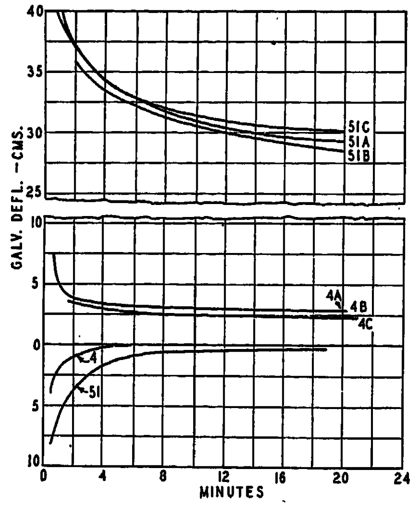

FIG. 12—D-C. CHARGE AND DISCHARGE CHARACTERISTICS FOR TWO DIFFERENT CABLE PAPERS

Set 4—paper No. 1
Set 51—paper No. 2

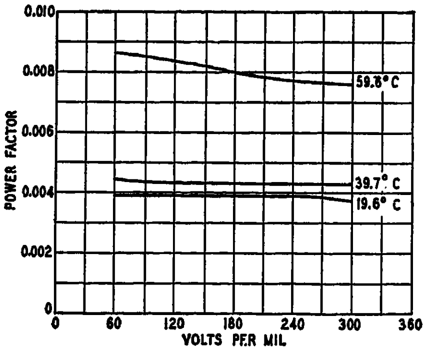

FIG. 13—RELATION BETWEEN POWER FACTOR AND VOLTAGE FOR PAPER NO. 3

Conference with the manufacturer resulted in a new shipment of compound which was put up in 50-gallon drums in an atmosphere of CO_2. This is the compound *B*. Arrangements were made in the laboratory for preventing the exposure of the compound to air. As compound was drawn from the drums CO_2 was admitted. The compound was exploded under vacuum before impregnation, as has been described, in order to remove the CO_2 and subsequently the compound, as well as the impregnated insulation, was held in an atmosphere of nitrogen until actually placed in the high-voltage test box. Throughout the use of this compound, covering a period of ten months, no evidence of deterioration was found.

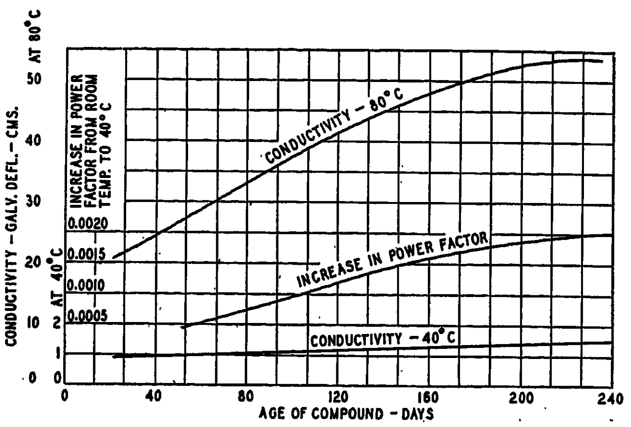

FIG. 14—CURVES SHOWING THE DETERIORATION OF COMPOUND WITH AGE DUE TO THE PRESENCE OF AIR

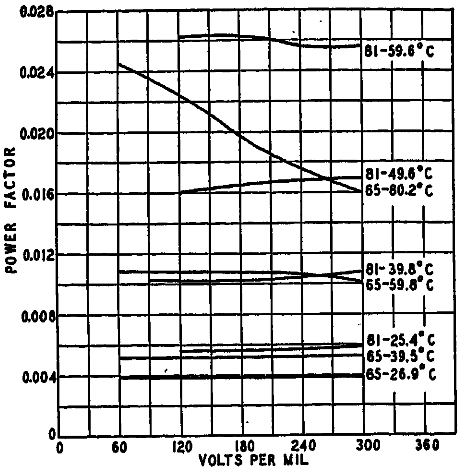

FIG. 15—RELATION BETWEEN POWER FACTOR AND VOLTAGE FOR PAPER IMPREGNATED WITH TWO DIFFERENT COMPOUNDS

Set 65—compound *A*
Set 81—compound *B*

It has been shown already that this compound gave a much longer life to the impregnated paper than the original compound *A*. A comparison of the two from several other standpoints is of interest. Fig. 15 shows a comparison of the power-factor voltage characteristics and Fig. 16 of the power-factor temperature characteristics. It is significant that here the power-factor characteristics give absolutely no clue to the life of the insulation, the insulation with the lower power factor having the shorter life. Figs. 6 and 7 show the variation of power factor during the life of the insulation. Although the power factor increases very slightly with the age of the insulation the increase does not become sharp except very near the time of breakdown. Hence neither the absolute value nor the shape of the power-factor voltage curve provide a certain indication of the condition or life of the insulation.

Variations in Structure of the Insulation

An examination of the results of the life tests, in the pressure range from 2 mm. to 2.5 cm., showed that small variations in material and assembly of the structure of the sample become quite important in this pressure region. Several tests showed quite clearly the importance of the tightness of the structure. The usual electrode of the samples consisted of a sheet of 1/64-in. sheet lead bound on by a layer of linen thread. In every case the lead was carefully smoothed and formed to the insulation and the thread was wrapped on as nearly as possible at the same tension. With this construction the longest lived specimen, impregnated at 2 mm., gave a life of 12,000 hours at 400 volts per mil.

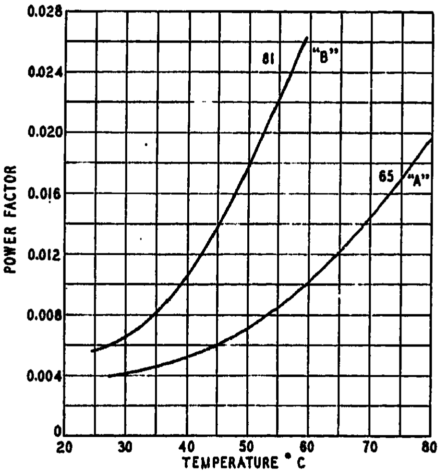

Fig. 16—Variation of Power Factor with Temperature for Paper Impregnated with Two Different Compounds

Set 65—compound *A*
Set 81—compound *B*

A sample was made up using, in place of the 1/64-in. lead, a sheet of lead foil 0.005-in. thick. This was bound on in the same manner as the 1/64-in. lead using the same thread tension. Due, however, to the thinness of the lead foil a much tighter construction resulted. The samples of this construction, impregnated not at 2 mm. but at 2.5 cm., showed lives of over 20,000 hours at 400 volts per mil, without failure. One specimen tested continuously at 800 volts per mil ran 188 hours in actual time, the equivalent of 48,200 hours at 400 volts per mil, without failure.

Acknowledgment

These studies were carried out in the School of Engineering at Johns Hopkins University with the support of the National Electric Light Association, through its subcommittee on Impregnated Paper Insulated Cable Research, Mr. W. F. Davidson, Chairman. For the continued interest and hearty cooperation of the members of this committee the authors extend their grateful appreciation. Acknowledgment is also made of the skill and devotion of Messrs. E. W. Greenfield and C. O. Newman, whole-time research assistants on the work.

Conclusions

The results reported in this paper conclude a somewhat extended investigation of the influence of small amounts of moisture and air on the properties of impregnated paper. The general conclusions, as related to the main purpose of the work, may be briefly stated:

The influence of residual moisture is universally bad and increasing amounts of such moisture are immediately reflected in higher values of power factor and loss and in other evidence of instability.

The chief importance of residual air is in its effect upon the life of the insulation. The smaller the amount of the residual air the longer the life. The accelerated life tests indicate, that so far as air content is concerned, under properly controlled conditions and with evacuation pressures well within reach in present day manufacturing methods, the life of impregnated paper may be extended to values far beyond those ordinarily supposed to pertain to the best present day cables. On the other hand, below a certain proportion of residual air, as represented say by complete impregnation at 1 cm. Hg. pressure, the further increase in life is not markedly great. This is due to the fact that below this value the increase in life due to reduced air is offset by normal and heretofore uncontrolled variations in the uniformity and quality of oil and paper. Low pressures of evacuation, therefore, are more important for the further withdrawal of moisture than for the extension of ultimate life as dependent on air content.

One of the most interesting conclusions is the evidence that flat power-factor voltage curves are obtained in insulation evacuated and impregnated at pressures up to 10 or 15 cm. Hg. The rising power-factor voltage curve commonly attributed to internal ionization is found only in poorly impregnated samples. There is some evidence that this type of curve may be caused by oil of originally poor quality in the presence of somewhat large quantities of air.

During the course of the work the successive steps in the control of several unforeseen variables have brought out much interesting information on the original and final properties of both paper and oil, the methods for their control, the stability of each, and other factors bearing on the properties of the completed product. Some of these are reported in the present paper and for others the foregoing papers must be consulted.

The conclusions of the present paper are briefly as follows:

1. The life of impregnated paper insulation increases steadily with a decrease in the amount of residual air.
2. For impregnating pressures above 2.5 cm. the life decreases rapidly with increasing pressure of impregnation. For pressures below 2.5 cm. the results show an increase of life of from 10 to 50 per cent between 2.5 cm. and 2 mm. impregnating pressure.
3. For impregnating pressures below 2.5 cm. normal variations in material and structure, particularly in the tightness of the structure, may offset the increased life due to decreasing the pressure of impregnation.
4. Cable compound deteriorates if it contains only a small amount of air even though it is kept in sealed containers, at room temperature. Air should be entirely excluded to avoid deterioration.
5. Flat power-factor voltage curves and the absolute value of power factor should not be accepted as indications of long life.
6. The power-factor rise due to the initial application of voltage during a life test is indicated as a possible criterion of insulation life.
7. A very satisfactory type of sample and reenforced end for accelerated life tests have been developed.
8. Narrow variations in the quality of both paper and oil may cause wide differences in the electrical characteristics and in the lives of the impregnated products.

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Discussion

For discussion of this paper see page 1447.

Insulation Variability

Its Influence in Determining Breakdown Voltages*

BY M. C. HOLMES†

Associate, A. I. E. E.

Synopsis.—The purpose of the paper is to describe a method of analysis for taking into account the effect of insulation variability in the determination of breakdown voltages and allowable operating stresses. The method is applicable to systems containing large areas of insulation, or large numbers of units of insulation in parallel.

General equations are derived, giving the breakdown voltage and number of failures to be expected, in terms of two parameters; the mean breakdown voltage and the variability of the insulation, both of which are determined from tests made on samples. It is shown how the results may be applied to the special case of electric power cables, for comparing the relative merits of different cables, and for determining the safety factor required to take account of the inherent variability and consequent unreliability of the insulation.

The necessity of considering the variability as well as the so-called strength of insulation is emphasized, and its importance brought out in terms of allowable operating stresses and failures.

A graphical method of analysis is described, which makes use of probability paper, changing the probability scale from "per cent" to "failures per hundred miles per year" in the case of cables.

Predictions of theory are compared with the results of practise, using results from experiments made to determine the effect of electrode area on breakdown voltage. Good agreement is shown between the two.

INTRODUCTION

IN 1927, in a paper by Messrs. Bush and Moon[1] the importance of the standard deviation as a measure of the inherent variability of insulating materials was pointed out. The standard deviation, sigma, is defined by the following equation:

$$\sigma = \sqrt{\frac{\Sigma\,(\delta)^2}{n}} \tag{a}$$

where $\Sigma\,(\delta)^2$ is the sum of the squares of the deviations of individual breakdown voltages from their mean, and n is the number of breakdown tests made. Sigma indicates the amount of scattering of the individual breakdown voltages and hence the variability of the material, test conditions being the same in each case. Small values indicate a uniform, homogeneous material; while large values indicate a non-uniform, variable material.

Curves, based on many thousands of breakdown tests, were given showing the manner in which breakdown voltages are distributed. It was shown that such voltages are distributed about the mean, E_a, approximately in accordance with the normal error curve,

$$y = \frac{1}{\sigma\sqrt{2\,\pi}}\, e^{-\frac{1}{2}\frac{(E - E_a)^2}{\sigma^2}} \tag{b}$$

the distribution being completely specified by the two parameters σ and E_a.

These two conceptions,—standard deviation as a measure of insulation variability, and normality of breakdown voltage distributions,—form the starting point and constitute the assumptions of the following theoretical development.

THEORETICAL CONSIDERATIONS

a. Coefficients of Variability and Uniformity,—Definitions. In specifying the variability of a material by the use of sigma, the mean must also be known. If the standard deviation, sigma, alone is given, no idea of the variability is gained, because the actual magnitudes of both sigma and the mean breakdown voltage E_a depend upon test conditions such as size and shape of electrodes, thickness of insulation, temperature, rate of application of voltage, etc. It happens, however, that both sigma and E_a vary in the same manner, since they both depend upon the same individual readings, so that their ratio remains the same. In other words, it is the ratio σ/E_a, or sigma expressed in per cent of E_a, which is a constant for a given material and which specifies its variability. The ratio σ/E_a, therefore, will be used here to represent variability. It will be called the "coefficient of variability" and will be represented by the symbol S. Its reciprocal, designated by the symbol H, may be taken as a measure of the uniformity of the insulation and called the "coefficient of uniformity."

b. The General Equations. Making use of the foregoing conception of variability and the assumption of normality in the distribution of breakdown voltages the following two general equations have been derived (see Appendix I for their derivation).

$$F = N\left[\frac{1}{2} - erf\left(\frac{1 - E_o/E_a}{S}\right)\right] \tag{1}$$

$$E_b = E_a\left[1 - S\,.\,erf^{-1}\left(\frac{1}{2} - \frac{1}{2\,N}\right)\right] \tag{2}$$

The first equation gives the number of failures, F, to expect in a system consisting of N units of insulation

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*Paper based on work done as a graduate student at the Massachusetts Institute of Technology.

†Asst. Prof. of Physics, West Virginia University, Morgantown, W. Va.

[1] For references see Bibliography.

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in parallel at an operating voltage E_o,—the units being removed from the system after failure. F is given in terms of the two parameters E_a and S, which taken together specify the quality of the insulation; E_a being the mean breakdown voltage of the units, and S the coefficient of variability. The second equation gives the breakdown voltage, E_b, to expect for a system of N units of insulation connected in parallel, in terms of the same two parameters E_a and S.

The symbol *erf* is an operator used to designate the Gaussian error function: thus, *erf* (k) is defined by the expression

$$erf\,(k) = \frac{1}{\sqrt{2\,\pi}} \int_o^k e^{-\frac{k^2}{2}}\,d\,k \qquad (3)$$

The symbol erf^{-1} represents the inverse operation: thus, erf^{-1} (k) means the quantity whose error function is k. These are well-known functions whose values have been computed and tabulated. They are analogous to the two symbols sin and $\sin^{-1}$, and their values may be obtained from tables[2] in a similar manner. They are not always designated by the symbols *erf* and erf^{-1}, however, but often simply by the expression (3) or by an equivalent expression.

In case error function tables are not available, equation (1) may be put in the form of an infinite series. Letting $(1 - E_o/E_a)/S = k$, for small values of k, equation (1) takes the form

$$F = \frac{N}{\sqrt{2\,\pi}}\left[\sqrt{\frac{\pi}{2}} - k + \frac{k^3}{2\,.\,3\,.\,\underline{|1}} - \frac{k^5}{2^2\,.\,5\,.\,\underline{|2}} + \frac{k^7}{2^3\,.\,7\,.\,\underline{|3}} - \,.\,.\,.\,.\right] \qquad (4)$$

This series is convergent, and the error is less than the last term retained.

For large values of k the above series converges too slowly for practical use, in which case it can be put in the following form:

$$F = \frac{N}{\sqrt{2\,\pi}}\;\frac{e^{-\frac{1}{2}k^2}}{k}\;[1 - k^{-2} + 1\,.\,3\,k^{-4} - 1\,.\,3\,.\,5\,k^{-6} + \,.\,.\,.\,] \qquad (5)$$

This is an "asymtotic" or semi-convergent series, but the error, again, is less than the last term retained.

c. Discussion. The two equations (1) and (2) are entirely general. They apply to all kinds of insulation, either in the form of continuous areas, as in cables, or in the form of discrete units, as in overhead transmission lines. In the former case N represents length of cable, measured in terms of some standard test length; in the latter case, N represents the number of units of insulation under voltage stress,—the number of strings of insulators along an overhead line, for example.

In the case of thin sheets of insulation, N represents area, and equation (2) gives breakdown voltage as a function of electrode area. Milnor's equation for the effect of electrode area,[3] $E_b = C_1 - C_2 \log A$, is an approximation to the probability expression for the same thing, obtained by considering the elementary areas, making up the total area A, indefinitely small and passing to the limit. It is valid only in cases where E_b is negligibly small compared with the mean breakdown voltage of the elementary areas. The two constants C_1 and C_2 are evaluated in each case by fitting a curve to data obtained from tests made on different size electrodes. The advantage of equation (2) over Milnor's equation is that it allows predictions to be made for any size electrode, from tests made on a single size, and in addition, takes into account the effect of insulation variability. The variability determines how great will be the effect of area. With perfectly uniform insulation, for example, area would have no effect on breakdown voltage.

A useful relation may be obtained by solving equation (1) for E_o; giving

$$E_o = E_a\,[1 - S\,erf^{-1}\,(1/2 - F/N)\,] \qquad (6)$$

an expression which gives the allowable operating stress corresponding to F failures per N units of insulation. Now, if F is taken as unity and N is taken as 10,000, for example, the operating stress corresponding to one failure per ten thousand units is given by the simple relation $E_o = E_a\,(1 - 3.72\,S)$, showing clearly the importance of the part played by the insulation variability in determining the allowable operating voltage for a given system. Similar expressions for different specified conditions may be obtained from the general equations, in like manner, by assigning particular values to the parameters. The extremely simple relation

$$E_o = E_a\,(1 - 4\,S), \qquad (7)$$

in the case of cables, gives the allowable operating voltage corresponding roughly to one failure per 100 miles of cable per year, where E_a is the mean breakdown voltage of standard 10-ft. test lengths reduced to one year basis (See Appendix II). Such a relation may be used for comparing the merits of different cables or made the basis of acceptance requirements and specifications.

In order to avoid misconception as to the scope or applicability of the present paper it should be emphasized that the foregoing theory takes account only of causes inherent in the insulation itself. It takes no account of external causes such as edge effect which might be encountered with different electrodes, nor of abnormal operating conditions such as surges and overloads which might be encountered in practise.

EXPERIMENTAL CONSIDERATIONS

a. Values of S Encountered in Practise. The following values of S have been calculated from the experiments of Hayden and Eddy[4] on the dielectric strength of oil.

Curve No.		S
I	Transil oil, 1 cm. spheres, 2 mm. apart	10.7 per cent
II	Transil oil, 1 in. spheres, 27 mm. apart	10.2 per cent
III	Transil oil, needle and 1 in. sphere, 2 mm. apart	9.85 per cent
IV	Commercial benzol, 1 cm. spheres, 2 mm. apart	6.4 per cent
V	Pure benzol, 1 cm. spheres, 2 mm. apart	4.82 per cent
VI	Air, 1 inch spheres, 1 cm. apart	1.94 per cent

Records of breakdown tests on other insulating materials, and on cable samples, are scattered throughout the literature. In general, breakdown tests made with air as a dielectric show the greatest uniformity and may be expected to result in values for S of 1 or 2 per cent. Such determinations include errors of measurements, as well as those due to irregularities in electrode surfaces, changes in pressure, temperature, etc. For tests made on thin layers of paper, cambric, etc., one may expect values ranging from 6 to 12 per cent. For the present day "solid" type of paper-insulated cable, values ranging all the way from 6 to 20 per cent may be obtained. A value as low as 6 per cent indicates a comparatively uniform insulation; while values as high as 20 per cent should be taken as an indication of poor, non-uniform insulation. Such conclusions also result from theoretical considerations based on the general equations, taking account only of the effect of variability: a value of 6 per cent indicates an allowable operating stress of approximately 75 per cent of the average breakdown stress E_a, whereas, for the same conditions (one failure per 100 miles of cable), a value of 20 per cent gives an allowable operating stress of only 17 per cent.

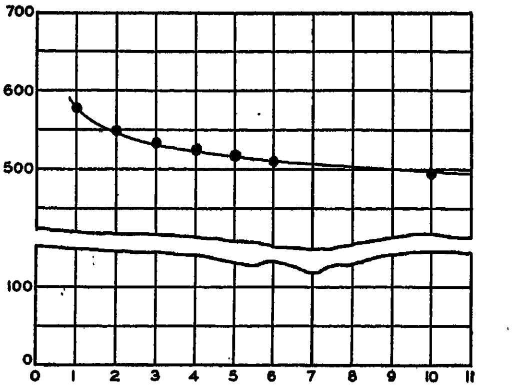

Fig. 1—Comparison of Theory and Experiment (from the Results of Moon's Experiments on the Effect of Electrode Area)

Tests made on 0.55 mil paper. Electrode No. 1. Run No. 91.
S = 8.25 per cent

b. Predictions of Theory Compared with Results of Experiment. Figs. 1 and 2 show curves comparing the predictions of theory with the results of experiment. Data for the first curve were obtained from Moon's experiments on the effect of electrode area.[5] The second curve is from Emerson and Webber's experiments.[6] They are both typical. The curves show the predictions of theory; the points show the results of experiments. The curve of Fig. 1 was calculated from the results of 917 breakdown tests represented in the initial point at unit area. In Fig. 2 each point represents the average of only 10 tests. For this reason the points are much more irregular. The theoretical curve fits the points as well as can be expected.

Summary

1. A general analytic method for the determination of failures, breakdown voltages, and operating stresses, taking account of the mean strength, variability and area of insulation, has been developed.

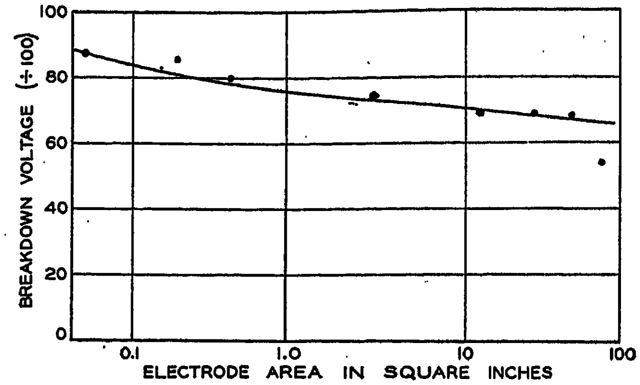

Fig. 2—Comparison of Theory and Experiment on the Effect of Electrode Area. (From Emerson and Webber's Experiments)

Tests made on 5 mil varnished cambric, using flat circular electrodes immersed in oil. Voltage raised 900 volts per second to failure. Average value of S = 6.9 per cent.

2. A good agreement is shown between the predictions of theory and the results of experiment.

3. The two factors, mean strength and variability, are equally important in the determination of allowable operating stresses and should always be considered in conjunction.

4. In the Appendix the conditions for accuracy and reliability have been investigated. It is shown that the accuracy depends upon the variability of the insulation itself as well as upon the number of specimens tested, decreasing rapidly with increase in variability. Ordinarily, fairly accurate determinations can be made from samples as small as twenty. Samples as small as ten may be used for obtaining indications of quality, but judgments based on fewer than ten tests would be of questionable validity.

5. A graphical method of analysis, making use of probability paper, is described in the Appendix. It furnishes a test for the normality of distributions and shows how non-normal distributions may be analyzed. A method for dealing with cable problems, where the additional factor of deterioration with time is important, is also outlined.

Appendix I

DERIVATION OF GENERAL EQUATIONS

a. Number of Failures. Consider a sample of n units of insulation, all of the same size, selected at random from a large lot and subjected to breakdown tests,—all tests being made under the same conditions. (The word "sample" is used here in the collective sense, meaning the entire collection of n units or specimens.)

Let:

n = number of units, or specimens, in the sample.

N = total number of units in the entire lot or system from which the sample has been selected.

E = voltage.

$E_1, E_2, \ldots . E_n$ = breakdown voltages of individual units.

E_a = average breakdown voltage of the n units.

σ = standard deviation calculated from test results.

Considering the distribution curve of breakdown voltages, the area under such a curve between any two values of voltage, such as A and B, represents the fraction of the n units failing between those two values, and is given by the expression

$$\frac{f_{AB}}{n} = \frac{1}{\sigma\sqrt{2\pi}} \int_A^B e^{-\frac{1}{2}\frac{(E-E_a)^2}{\sigma^2}} . \, d\,E \tag{8}$$

where f_{AB} is the actual number of failures occurring between A and B. The total area under the curve, therefore, equals unity, and the two areas on either side of E_a each equals ½. The expression for the fractional number of failures between $E = O$ and any voltage E, then, is given by the expression

$$\frac{f_E}{n} = \frac{1}{2} - \frac{1}{\sigma\sqrt{2\pi}} \int_E^{E_a} e^{-\frac{1}{2}\frac{(E-E_a)^2}{\sigma^2}} . \, d\,E \tag{9}$$

where f_E represents the actual number of failures corresponding to the voltage E. For the entire system of N units, and an operating voltage E_o, this will correspond to a number of failures given by the expression

$$F = \frac{N}{n} f = N\left[\frac{1}{2} - \frac{1}{\sigma\sqrt{2\pi}} \int_{E_o}^{E_a} e^{-\frac{1}{2}\frac{(E-E_a)^2}{\sigma^2}} . \, d\,E\right] \tag{10}$$

This expression may be written in a much simpler form by introducing a new variable $k = (E_a - E_o)/(\sigma) \doteq (1 - E_o/E_a)/(S)$, multiplying by $d\,E/d\,k = -\sigma$, to take account of the change of variable, interchanging the limits of integration and changing the sign at the same time, giving

$$F = N\left[\frac{1}{2} - \frac{1}{\sqrt{2\pi}} \int_0^k e^{-k^2/2} . \, d\,k\right] \tag{11}$$

and finally, in still more compact form,

$$F = N\left[\frac{1}{2} - e\,r\,f\,(k)\right] \tag{12}$$

$$= N\left[\frac{1}{2} - e\,r\,f\left(\frac{1 - E_o/E_a}{S}\right)\right] \tag{13}$$

b. Breakdown Voltage. From the distribution curve of breakdown voltages it is evident that at a voltage corresponding to the mean, E_a, approximately one-half the total number of units considered will have failed. If the size of unit is taken as N, and F in equation (12) is taken as 1/2, the value of voltage, E_o, implicit in the expression will represent the mean breakdown voltage of systems consisting of N of these units. Doing this, there results

$$1/2 = N\,[\,(1/2) - e\,r\,f\,(k)\,] \tag{14}$$

Transposing,

$$e\,r\,f\,(k) = (1/2) - (1)/(2\,N) \tag{15}$$

From which,

$$k = e\,r\,f^{-1}\left(\frac{1}{2} - \frac{1}{2\,N}\right) \tag{16}$$

Putting for k its value $(1 - E_o/E_a)/(S)$, and replacing E_o by the symbol E_b, now, to denote mean breakdown voltage of systems containing N units of insulation, there results the equation

$$(1 - E_b/E_a)/(S) = e\,r\,f^{-1}\left(\frac{1}{2} - \frac{1}{2N}\right) \tag{17}$$

Whence, solving for E_b,

$$E_b = E_a\left[1 - S\,e\,r\,f^{-1}\left(\frac{1}{2} - \frac{1}{2N}\right)\right] \tag{18}$$

Appendix II

APPLICATION TO ELECTRIC POWER CABLES

It is in the field of electric power cables, where huge areas of insulation are exposed continually for years at a time to high-voltage stresses, that the question of variability is of the greatest importance. Probably it is in this field that the theory may be most advantageously applied.

In applying the theory to cables an additional factor must be taken into account; namely, the influence of time. Experiments on the deterioration of oil-impregnated cable insulation under voltage stress have shown that the life varies approximately inversely as the seventh power of the voltage stress[7] for three-conductor cable. It has been suggested, in the N. E. L. A. report for 1926-27, that all breakdown tests on cable be referred to the same time basis by means of the so-called inverse seventh power relation. Unfortunately the relation has been verified only for times up to about 1,000 hours. The decrease in breakdown voltage from 1,000 hours to one year, indicated by the inverse seventh power relation, is only 25 per cent (*i. e.* from 100 to 75 per cent). Probably no great error will result, therefore, from assuming it to hold for times up to one year,—at least that is the only way available at present for estimating the effect of time. In the case of cables, then, the breakdown voltages are assumed to be referred to some common time basis before calculating the effect of length and variability. This relation may be written, $E = E_1 t^{-1/7}$, where E is the breakdown voltage for the time considered, E_1 is the breakdown voltage for unit time, and t is the number of units of time to which E_1 is to be referred.

Illustrative Problem. Suppose a number of long-time breakdown tests to have been made on standard 10-ft. samples of cable and referred to some common time basis, say 100 hours, and that the results indicate a mean breakdown voltage E_a of 220 volts per mil and a variability S of 12 per cent. Let it be required to determine the allowable operating stress for such cable, assuming one failure per 100 miles of cable per year.

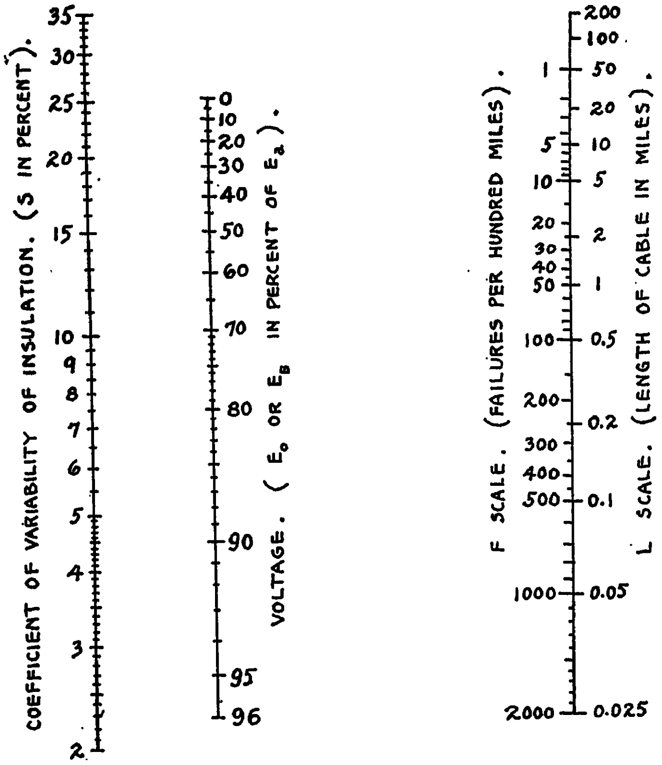

FIG. 3—ALINEMENT CHART FOR ELECTRIC CABLE CALCULATIONS. (BASED ON 10-FT. TEST SAMPLES)

Giving: (*a*) Breakdown voltage as a function of length and variability
(*b*) Failures in terms of operating voltage and variability

Voltage scale represents: (*a*) Operating voltage when used with *F* scale
(*b*) Breakdown voltage when used with *L* scale

The reduction in stress, for taking account of insulation variability, is made using equation (7) as follows:

$$E_o = E_a\,(1 - 4\,S) = 220\,(1 - 4 \times 0.12)$$
$$= 114.4 \text{ volts per mil}$$

A further reduction, for taking account of time, may be made, reducing the 114.4 volts per mil from a 100-hour basis to a 1-year basis. If this is done by means of the inverse seventh power relation the final value of E_o becomes,

$$E_o = 114.4\,t^{-1/7} = 114.4 \times (87.6)^{-1/7} = 60.4 \text{ volts per mil}$$

The final value of E_o thus found considers only the effects of insulation variability and time. It is therefore the upper limit. If it is exceeded, more than the allowed one failure per 100 miles of cable may be expected. It should be noted that the inverse seventh power law is used here merely for an illustration, suggesting how the time factor may be taken care of. If a sixth power or some other law should be established at some future time it can be used in place of the one used here. It is the purpose of this paper merely to show the dependence of the operating stress upon insulation variability. The foregoing should not be taken as an argument either for or against the seventh power relation. As an example of the magnitude of the difference involved it may be of interest to note that if an inverse sixth power law is used in place of the seventh, the final value of E_o becomes 54.4 volts per mil instead of 60.4 volts per mil.

Computations. An alinement chart for convenience in calculating cable problems is given in Fig. 3. The chart is for standard 10-ft. samples but may be used for other lengths by applying the proper correction factors. For example, if test samples of x ft. instead of 10 ft. are used, the number of failures, F, obtained from the chart must be multiplied by the ratio $10/x$.

The use of the alinement chart may be illustrated by the following example. Suppose it is desired to find the per cent decrease in operating voltage to allow for a five-mile length of cable whose insulation has a coefficient of variability, S, of 14 per cent. A straight edge is laid on the chart so that it intersects the S scale at 14 and the L scale at 5. The intersection on the voltage scale then gives 50, indicating a necessary reduction in operating voltage of 50 per cent.

Appendix III

A GRAPHICAL METHOD OF ANALYSIS

Probability paper furnishes what is undoubtedly the simplest and most powerful method of analyzing a given set of test data. It was developed in 1914 by Mr. Allen Hazen[8] while studying variations in annual run-off of streams, for the purpose of predetermining the sizes of impounding reservoirs required in municipal water supplies. The rulings on one of the coordinates are spaced in accordance with the normal law of error, so that data which follow the normal law will form a straight line when plotted cumulatively on such paper.

In order to illustrate its use a specific example will be considered. Fig. 4 shows a hypothetical set of data, representing the results of 50 breakdown tests, plotted on such paper. The voltage gradients at breakdown are assumed to have been calculated and tabulated in ascending order of magnitude, and the results plotted cumulatively in the same order. Abscissas represent breakdown stress, while ordinates represent failures in per cent of the total number of specimens tested. With 50 as the total, the first one will represent 2 per cent, the second 4 per cent, etc. Any point, however, is indeterminate between 2 per cent limits. It is customary, therefore, to plot each point in the middle of its range of indeterminancy. Thus, the first one, which failed at a stress of 45 volts per mil, is plotted on the 1 per cent line, the second one on the 3 per cent line, etc.

The abscissa, at the point where the curve cuts the 50 per cent line, represents the mean, or median, breakdown stress E_a of the samples. The slope is a measure of the coefficient of variability, S, of the insulation. A perfectly uniform material would plot as a vertical line.

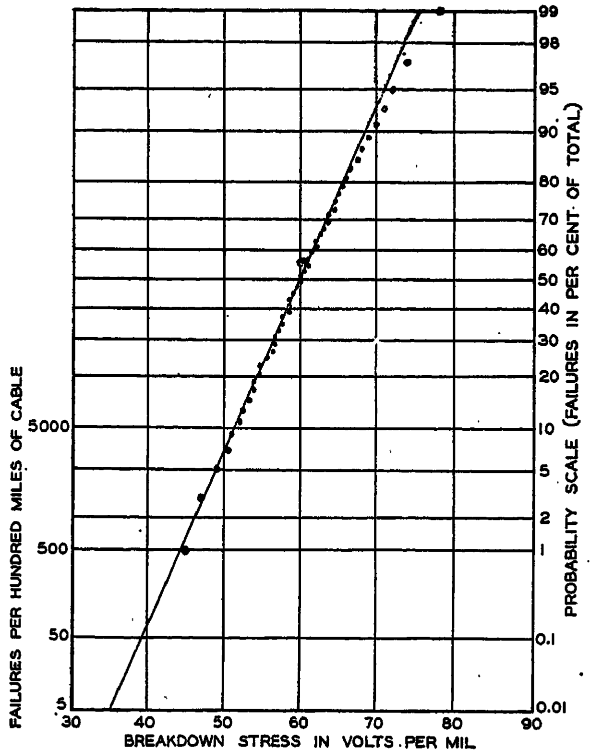

FIG. 4—HYPOTHETICAL SET OF BREAKDOWN TESTS PLOTTED ON PROBABILITY PAPER

An auxiliary scale, making use of the fact that the most probable number of events is equal to the probability of a single event multiplied by the total number of possible events or trials made, may be constructed. For example, if in the present problem each cable specimen had been 10.5 ft. long, 100 miles of cable would correspond approximately to 50,000 such units and the 10 per cent line would represent 50,000 × 0.10 = 5,000 failures per 100 miles of cable, 1 per cent would correspond to 500 failures, etc. Such a scale is shown at the left margin of Fig. 4.

Some of the essential points of the theory are brought out when the data are plotted thus on probability paper. For example, if the curve is extended downward to the working range, around 5 failures at 35 volts per mil, it is evident that the process is one of extrapolation, as are all sampling processes. It shows the necessity for considering both the mean breakdown voltage *and* the variability. Also, it will be noted that the upper points do not fall on the same straight line formed by the lower set of points. This means that only the lower half of the distribution follows the normal law and shows how data may be analyzed even though they do not follow the normal law as a whole, as was assumed in the derivation of the equations. It also shows the relative unimportance of samples representing high dielectric strength.

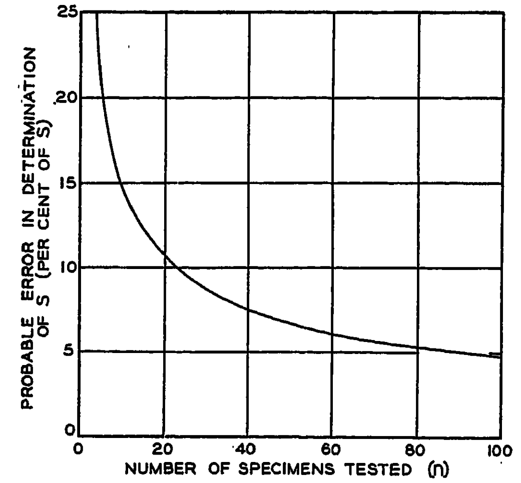

FIG. 5—PROBABLE ERROR IN THE DETERMINATION OF S AS A FUNCTION OF THE NUMBER OF SPECIMENS TESTED

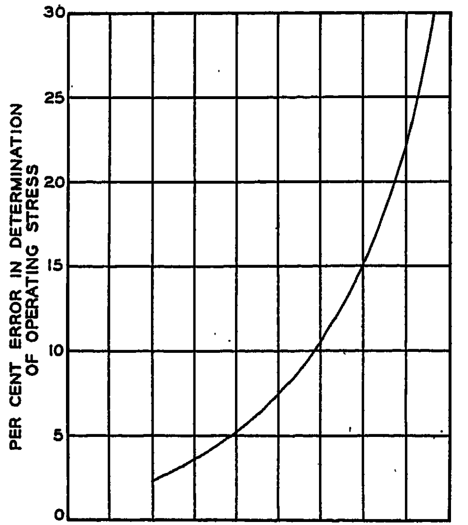

FIG. 6—ERROR IN DETERMINATION OF ALLOWABLE OPERATING STRESS AS A FUNCTION OF S

(For samples consisting of twenty test specimens)

Appendix IV

ACCURACY AND RELIABILITY

In statistical work, it is customary to employ a quantity known as the probable error to indicate the accuracy of a determination made from a series of observations. The probable error is defined as the deviation, on either side of the mean, such that half of the observations are included within such a range. Thus, $x = 12.73 \pm 0.27$ means that the quantity x has been determined by statistical processes, such as averaging, to be 12.73 with a probable error of 0.27; or, it is an even bet that the true value of x lies between 12.46 and 13.00, and that the odds are three to one that x is not greater than 13.00.

Error theory considerations give the probable error in determining the mean, by sampling processes, as $0.6745\, \sigma / \sqrt{n}$, where σ is the standard deviation of the lot from which the sample is drawn, and n is the number of specimens in the sample. The probable error in the determination of the standard deviation is $0.6745\, \sigma / \sqrt{2n}$.

Based upon these relations the curves of Fig. 5 and Fig. 6 have been drawn. Fig. 5 shows the probable error in the determination of S as a function of n, the number of specimens tested. Based upon the curve of Fig. 5 the accuracy in determining allowable operating stresses, for samples consisting of 20 test specimens, has been calculated. Standard 10-ft. specimens and an operating stress based upon one failure per 100 miles of cable are assumed. The results are shown by the curve of Fig. 6.

From the results it is seen that the accuracy obtainable depends upon the quality of the insulation as well as upon the number of specimens tested, the error increasing rapidly for variabilities greater than 14 or 15 per cent. Thus, for a given required accuracy, it is more expensive to test poor cable than to test good cable.

List of Symbols

F = number of failures.
erf = an operator used to denote the gaussian error function.
erf^{-1} = an inverse operator, analogous to $\sin^{-1}$.
E_o = operating voltage.
E_b = breakdown voltage.
E_a = mean breakdown voltage of test specimens.
S = coefficient of variability = standard deviation expressed as a decimal fraction of E_a.
H = coefficient of uniformity = $1/S$.
$k = (E_a - E_o)/\sigma = (1 - E_o/E_a)/(S)$.
n = number of test specimens in sample.
N = general symbol used to represent number of units of insulation, the unit being the size of test specimen, = area in the case of sheet insulation, length in the case of cables, and number of insulators in the case of overhead lines.

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Discussion

ECONOMICS OF HIGH-VOLTAGE CABLE

(Roper)

CHARACTERISTICS OF OIL-FILLED CABLE

(Shanklin and Buller)

OIL-FILLED CABLE AND ACCESSORIES

(Atkinson and Simmons)

RESIDUAL AIR AND MOISTURE IN IMPREGNATED PAPER INSULATION—III

(Whitehead and Hamburger, Jr.)

INSULATION VARIABILITY

(Holmes)

G. B. Shanklin: Mr. Holmes' work is of the highest order, theoretically. There are many different factors that might and do cause cable failures in service. Mr. Holmes' theory would be applicable only in the case of inherent insulation failures uniformly produced by overstressing the dielectric under the particular conditions assumed. Few if any failures in modern cable are due to this cause.

The paper by Dr. Whitehead and Mr. Hamburger is a very valuable contribution to our knowledge of the effects of gas and moisture, as well as other impurities, when allowed to exist in high-tension cable. I do not think we need any additional evidence to prove the desirability of eliminating all traces of gas and other impurities, both free and in solution, and preventing their after occurrence in service. The results presented in this paper, as well as other experiences, are too convincing. The whole principle of the oil-filled cable is based on this.

This paper does not, however, show us *how* to eliminate impurities. High vacuum during the drying operations is certainly not the entire answer, as far as initial factory impurities are concerned. Nor do I believe that results obtained in a university laboratory can be used reliably as a practical guide for factory production methods. In removing impurities from cable, each manufacturer has his own distinct problems, depending upon the kind of materials and production equipment used. It would be impossible to have a standardized process equally and safely applicable to all manufacturing plants. Cable quality should be judged by the principles followed and results obtained. Any other criterion would be decidedly dangerous.

The paper by Messrs. Atkinson and Simmons is in good agreement with our own in the conclusion that oil-filled cable is the right answer for high-voltage service. My comments are confined to the condenser principle so cleverly introduced in their joint and terminal designs. There are undoubted possibilities in the use of this condenser principle. This idea is not employed in our present designs of stop joints, normal joints and terminals, and the reliability of these is well proven by several years of successful service. To meet this competition the condenser designs must prove equally good, or better, electrically and mechanically, and of equal or lower cost. Compactness is also a factor to be considered. In my opinion, the condenser principle is more applicable to stop joints than to normal joints and terminals. In the interests of progress the comparative advantages and disadvantages of these designs should be carefully weighed. Additional experience will indicate the right trend.

We have carefully checked the economic data given by Mr. Roper and have few suggestions or criticisms that would add to their value.

As Mr. Roper ably points out, an economic comparison of ordinary "solid" cable and oil-filled cable reaches its highest point of interest at a voltage rating of 66,000. This might be summed up briefly by saying that oil-filled cable is more economical than solid cable above 66-kv. rating. Also, 66-kv., three-conductor, oil-filled cable is more economical than single-conductor, solid cable up to 50,000-kva. per circuit. With the exception of 45-kv., three-conductor, oil-filled cable, solid cable is the more economical below the limits outlined above. The economic dividing line at the present time, that is of real interest, has to do with 66-kv., single-conductor cable of 50,000-kva. per circuit and higher.

The comparison in Mr. Roper's paper would indicate that within this range single-conductor, solid cable is slightly more economical than oil-filled cable, although he points out that only a small reduction in cost of oil-filled would place the two on an equitable basis. Even since Mr. Roper prepared the data for his paper there have been reductions in cost of 66-kv. oil-filled lines. This has been accomplished as follows:

(a) Reduction in insulation thickness from 0.40 and 0.42 inches to 0.35 and 0.375 inches. This has reduced the comparative cost of cable from 2 to 5 per cent.

(b) A reduction of approximately 25 per cent in cost of oil reservoirs due to simplifications in production.

(c) Increase in guaranteed maximum copper temperature from 70 to 75 deg. cent.

A comparative cost tabulation is given below in which these reductions are included. All other items are as presented by Mr. Roper. His cost of 66-kv., single-conductor cable is used as a standard of reference and the cost of oil-filled is expressed as a percentage of this.

ECONOMIC COMPARISON OF SINGLE-CONDUCTOR, 66-KV., SOLID AND OIL-FILLED CABLE LINES: RELATIVE INVESTMENT COST—NO TERMINAL

Kva. rating	Solid 60° C. copper 15° C. earth D. W. Roper	Oil-filled 70° C. copper 15° C. earth D. W. Roper	Oil-filled 70° C. copper 15° C. earth revised	Oil-filled 75° C. copper 15° C. earth revised
50,000	100%	115.5%	113.5%	113.0%
75,000	100%	106.0%	105.5%	102.0%
100,000	100%	103.5%	100.0%	95.4%
125,000	100%	105.0%	100.0%	96.0%

Because of higher copper loss the annual cost is more favorable to solid cable, but I think this tabulation shows clearly that progress is being made and that eventually the cost of 66-kv. oil-filled cable will in all cases be less than solid. At the present time it is less only for loads below 50,000 kva. and above 100,000 kva.

Mr. Roper, as everyone knows, is a strong advocate of reduction in insulation thickness as a means of further cost reduction. It is an obvious duty of the manufacturers to cooperate as far as judgment dictates. There has been material reduction in insulation thickness of solid cable in recent years and as already pointed out there has been a corresponding reduction in oil-filled cable. In my opinion it would be a mistake to move too rapidly in this direction.

When all possible angles of the situation are considered, it is an open question whether the additional cost reduction that might be accomplished in this way is sufficiently noticeable to compensate for the undoubted sacrifices involved. Reduction in cost of accessories, methods of installation, conduit structure, etc., have greater possibilities.

As an example, assume that the cost of solid cable is reduced 5 per cent by a corresponding reduction in insulation thickness. This means only a saving of about 2.5 to 3 per cent in over-all cost, but it means a far greater reduction in factor of safety. No one would hesitate to pay this much for an insurance policy covering a lesser risk. What I wish to bring out is that a reasonable margin in the way of insulation thickness is a very cheap form of insurance.

It must be considered also that operating requirements are, today, very exacting. More than two or three failures per 100 miles of cable per year is considered a rather poor record and the manufacturer's reputation suffers accordingly. This obviously demands a greater factor of safety than an acceptance of, say, 25 failures per 100 miles per year.

F. A. Brownell: It seems highly improbable that a mathematical solution such as given in Mr. Holmes' paper could be applied to determine the number of failures of a material as temperamental as a power cable. But with more uniform manufacture of cable it seems plausible that the law of probability might be applied where data were based on a relatively large number of test specimens.

We have some very good data on the behavior of cables both under test conditions and in service. The results of the tests of 28 fifteen-foot specimens of cable made by three different manufacturers were used to determine the variability factor and the equivalent volts per mil per year. The variability factor was found to be 4.7 per cent and by using the inverse 6th power law the equivalent volts per mil per hour were 353 or 78 volts per mil per year. This value is somewhat low as compared with the results obtained at other laboratories.

The value of F the number of failures per 100 miles per year was 0. In 1930 the Public Service Electric & Gas Co. of New Jersey had 99.72 mile years of this type of cable in operation with no inherent cable failures.

Using the graphic method on page 1445 with $S = 4.7$ per cent and one failure per 100 miles of cable we find an allowable operating voltage of 80 per cent of E_a or 62.5 volts per mil per year or 37 kv., three-phase. This seems reasonable and in line with Mr. Roper's recommendation of operating our cables at a higher stress than at present.

The cable operates at 44 volts per mil a value which is 56 per cent of E_a the mean breakdown voltage. Assuming one failure per 100 miles of cable, a line through these two points gives a coefficient of variability $S = 11$ per cent which would allow a considerable variation from the mean in our test results.

W. B. Kouwenhoven: Mr. Roper's paper presents a very valuable contribution to the cable art. In Fig. 31 of his paper he shows that there is an improvement in power factor with time. These curves are very interesting and are accompanied by a fall in the ionization factor as shown in Fig. 32.

At the School of Engineering at Johns Hopkins University we are conducting an experimental investigation on cable characteristics, supported by the Utilities Research Commission of Chicago. In this investigation we are determining the electrical characteristics of the oil alone, the paper alone, and then the characteristics of the impregnated paper. In addition to the a-c. measurements we are also taking oscillograms of the charge and discharge curves under d-c. potentials.

In a number of specimens we have noticed an improvement in power factor following impregnation. This improvement has continued over a considerable time before the power factor reached a constant result. An analysis of the charge and discharge curves taken under d-c. potentials shows that this reduction in power factor and the corresponding reduction in loss is accounted for by a lowering of the initial conductivity of the impregnated material. This reduction in conductivity may be due to the adsorption of ions by the paper or to some other reason not understood. We are continuing our investigation.

K. W. Miller and F. O. Wollaston: Messrs. Shanklin and Buller's solution of the oil flow and temperature transient problem by means of the Heaviside operator is ingenious. However, it would be unfortunate if the impression was left that for complete solution this type of analysis is necessary. The same solution can be obtained by well-known methods of elementary differential equations, which we prefer for two reasons:

(a) The mathematical processes are more familiar to most engineers and at every step the physical interpretation of the equations is evident.

(b) The solution in this case can be made more compact in form without omitting essential steps and without loss of complete generality.

Equation (1) given by Shanklin and Buller is somewhat inaccurate, since the dielectric loss is considered to occur at the conductor (see equation (2)), instead of being distributed throughout the insulation. Miller's solution of this problem includes the correct distribution of the dielectric loss, which introduces an additional logarithmic term in X. For high-voltage cables, especially 132 or 220 kv., incorrect use of the dielectric loss term produces considerable error in the oil demand curves. To correct this would unduly complicate Shanklin and Buller's equation (2), which they obtain by methods of Heaviside.

When the Heaviside method is used for finding the constants of integration A_n, equation (1) will fit the boundary conditions perfectly when, and only when, all values of n between one and infinity are employed. This is quite impractical to do, and usually only about three values of A_n would be calculated. This being so, it is obvious that the boundary conditions would no longer be perfectly satisfied, although the approximation may be very good. Since for practical reasons only about three values of A_n would be used, we found it more convenient, and more accurate, to set up three simultaneous equations in A_n, and force them to fit the boundary conditions at known selected points of chief importance. Incidentally, this method avoids all difficulties in properly providing for the correct distribution of dielectric loss.

The solution of practical problems has convinced us that obtaining the roots of equation (4), which also appears in our form of solution, is a long and laborious task. We have, therefore, made some mathematical transformations, which allowed us to prepare convenient charts from which the roots (K_n) can be obtained in a few minutes.

After obtaining the roots, one proceeds to compute coefficients A_n. Using Shanklin and Buller's method, equation (2) would have to be evaluated three times. Using our method of three simultaneous linear equations, we found the process relatively simple. We have prepared charts from which all the numerical values necessary are obtained directly, and only a few minutes of elementary algebra are required to get the values of A_n.

We find that the superposition principle is valid throughout. Shanklin and Buller have pointed out that the total oil demand is the sum of the conductor, sheath and insulation demands, which are computed separately. We would like to point out that one can compute the effect on temperature or oil demand for a unit amount of copper loss, dielectric loss, or sheath loss separately. Then for ten times as much copper loss, the corresponding part of the answer would be multiplied by ten, and likewise for dielectric and sheath losses. To get the total effect of any combination of losses, one adds the effects of each one acting separately. Once the computations are made on that basis, the results for any specific set of conditions, such as dropping load with or without removal of voltage, effect of sheath losses, etc., are very easily obtained without repeating the labor of solving all the equations.

It might be remarked that the computations for oil demands using Shanklin and Buller's equation (6) generally would be long and tedious. In our form of solution it turns out that the terms which at this point require the most labor to compute also appear in the simultaneous equations for A_n. When we prepared our charts to eliminate the labor from solving the simultaneous equations, we also got rid of the difficulties in solving both for oil demands and cable temperatures.

The paper provides only for load which changes instantaneously and thereafter remains constant at the new value. We have generalized the solution to take care of loads varying in any manner whatever. Church[1] obtained a solution for the generalized case, but the resulting expressions were only approximate, and difficult to evaluate numerically. The additional terms contained in our general solution fortunately are very simple functions of the load curve, and are easily handled.

With the labor saving charts we have prepared, no knowledge whatever of the properties of Bessel functions is required of the computer, and not even a table of their numerical values. Using our methods and aids, the saving in labor of computation is tremendous. At a conservative estimate, it would require at least a week for the uninitiated to compute and verify a complete solution for one cable, using Shanklin and Buller's equations. With our simplified process and graphical helps, this can be reduced to a few hours without any sacrifice in accuracy, a considerable gain in flexibility, and greatly reduced hazard of error.

The results, referred to above, of our development of this problem since Miller solved it in 1927, will be made available to those interested.

Wm. A. Del Mar: This paper, like several others by Mr. Roper, is both a milestone and a direction sign.

As a milestone it gives the present commercial status of various types of cable. Perhaps the most important point brought out in this part of the paper is that, for Chicago conditions, 66 kv. single-conductor oil-filled cables can now compete with cables of the ordinary type for winter ratings between 40,000 and about 115,000 kva. It should not be forgotten, however, that this conclusion applies only to the flat topography of Chicago. Corresponding estimates for more hilly localities would raise the limits of voltage and power up to which cable of the ordinary type would be economical.

Mr. Roper's direction sign points to simplification of the oil-filled cable. Two other papers on this subject in this group bear this out. My own work, along rather different lines, also points in the same direction. An essential feature of any scheme of simplification is, I believe, the use of shipping reel reservoirs for cables impregnated at the factory with liquid oil. This idea, however, was developed many years ago and subsequently patented, in connection with the high-tension cable system of the company with which I am connected.

Another of Mr. Roper's direction signs is toward an elastic sheath to compensate for expansion and contraction. This presumably involves the development of a material or structure which, in addition to having the general characteristics required for a sheath, is elastic circumferentially and plastic longitudinally. Such a sheath is not yet in sight.

Mr. Roper's plea for thinner insulation on cables of ordinary type is based on the fact that the commercial run of such cables is considerably below both laboratory made samples and some factory made lengths of outstanding merit. With careful supervision, he assumes, the general run might be made of this superior quality. This may and probably will be accomplished in time, but I believe that, at the present time, the thicknesses which the American manufacturers approve, are the least safe thicknesses for general American conditions. It is pleasing, however, to know that Mr. Roper is prodding the manufacturers in this matter, because it gives an added zest to our development work, and will help in approaching the ideal cable which is always a thing of the future.

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[1] *Temperatures in Electric Power Cables under Variable Loading*, by Elwood A. Church, TRANS., A. I. E. E., Sept. 1931, p. 982.

The oil-filled cable has two distinguishing characteristics, of which only one is usually stressed, namely, its "breathing" under varying load. The other property is, in my opinion, of even greater importance, namely, its high dielectric strength over long periods of time, or, in other words, its comparatively flat voltage-time curve combined with a short period dielectric strength at least as high as that of a cable of ordinary type. This, also, as pointed out in my discussion of the Whitehead and Hamburger paper, is due to the mobility of its oil, but we should carefully distinguish between the two properties, interrelated as they are.

The flat voltage-time curve is due to local characteristics of the cable and has nothing to do with hollow cores, reservoirs, stop-joints, etc. When cable cools, especially after the high temperatures of manufacturing, the contracting oil tends to concentrate in the thin passages where the capillary attraction is greatest, and to draw away from the larger passages where the attraction is least. These passages, in the order of their capillary attraction, are as follows:

1. Spaces between fibers of paper.
2. Spaces between flat surfaces of paper tape.
3. Spaces between edges of paper tapes.
4. Spaces between strands of conductor and space between insulation (or shield) and sheath.

There are two opposing sets of forces during contraction, the net capillary attraction and the viscous resistance. In the cable of ordinary type, these forces balance somewhere between items (1) and (3) of the above list; usually between (2) and (3). In the oil-filled cable, on the other hand, the balance is between (3) and (4).

The "breathing" ordinarily discussed is the oil flow in and out of the cable through especially provided passages, and its function is to keep the strand spaces or oil channels filled, these latter being the real reservoirs of the oil-filled cable.

Another feature of the single-conductor oil-filled cable which is more or less taken for granted, is that the very possibility of the use of breathing reservoirs depends on some open passageway being made, at the splices, between the reservoir and the hollow core. The problem is to place this passageway where it will not weaken the joint by promoting tangential leakage. Mr. Shanklin and his associates accomplish this by using pairs of terminators instead of joints of the ordinary type. Messrs. Simmons and Atkinson eliminate tangential stresses in the oil passageway by the use of stress directive condensers.

The following discussion assumes that where the authors (Dr. J. B. Whitehead and F. Hamburger, Jr.) refer to "impregnation pressures" they mean "evacuation pressures." It is the different evacuation pressures which change the air content. The small range of low impregnation pressures always ending with a period at one atmosphere, cannot appreciably affect the air content, as the cable is covered with oil during this phase of the process. There is, of course, no reason why the impregnation pressure should be related in any way to the evacuation pressure. My reasons for calling attention to the matter are both to save readers of the paper from misunderstanding it and to suggest to the authors that they extend their experiments to ascertain the effect of a wide range of impregnation pressures on the residual air content, using a constant evacuation pressure.

Some manufacturers impregnate their cables under a high pressure, say 100 lb. per sq. in. or more, after the vacuum treatment. Such pressures may affect the distribution of free air content by causing the free air to go into solution in the oil, from which it would be partly thrown out, but more evenly distributed, when the impregnating pressure is removed. The authors assume that their impregnation pressures are equal to their evacuation pressures, but this is not strictly true, as with the vertical impregnating tank, which they employ, the impregnating pressure at the bottom of the sample is never less than several additional centimeters of mercury, due to the head of oil.

The reinforced end with logarithmic flare, described by the authors, was suggested several years ago by Mr. C. F. Hanson and further developed by Mr. John H. Palmer, whose discussion gives some design details.

The authors call attention to a very important point in connection with the parallel testing of cables. It has long been known that voltage rises occur due to resonance when two or more reels of cable are tested simultaneously at high voltage. That similar effects could occur due to the multiplication of test samples four feet long, is very surprising. I believe the authors might, with great advantage, follow up the clue suggested by these experiments. It might lead to very important developments.

An investigation was made recently by Mr. John H. Palmer, of the effect of corona on test voltage, by means of Lichtenberg figures.

The high-voltage transformer was rated at 150 kv. and 150 kva. This was connected by a small wire about 6 in. long to a 1¼ in. diameter bus. This bus was approximately 20 ft. long. It passed through a wall with a wall type bushing and had a right angle bend near its end. The ends of the bus were originally rough and unfinished. Before the following tests were made, however, all of these rough corners and ends were rounded and smoothed off with plastic wood and then given a coat of conducting paint. All small conductors were replaced with ones of large diameter. When this was done, no corona was visible at voltages below 90 kv. There was considerable corona, however, visible at voltages above 100 kv.

The apparatus used for obtaining the Lichtenberg figures consisted of a small, light tight wooden box with an electrode projecting through the top. It was electrostatically shielded by lead foil over the outside, which also acted as the ground electrode. Photographic film was placed under the high potential electrode. A pillar type insulator having six petticoats was used as a potentiometer. This was set on a grounded metal plate and had a 2 ft. diameter shielding ring on the top. The top was then connected to the bus by a large diameter lead and the indicator was connected across the lower petticoat.

Tests were made at 60, 80, 100 and 125 kv. on the bus alone, and on the bus plus about 20 ft. of No. 22 A.W.G. copper wire to produce corona. Tests were also made with two cables (15 ft. long under the lead) as load, at 60 and 80 kv. These cables were single conductor No. 4/0 with 220-mil impregnated paper insulation. They were connected to the bus by means of approximately 20 ft. of No. 22 A.W.G. wire.

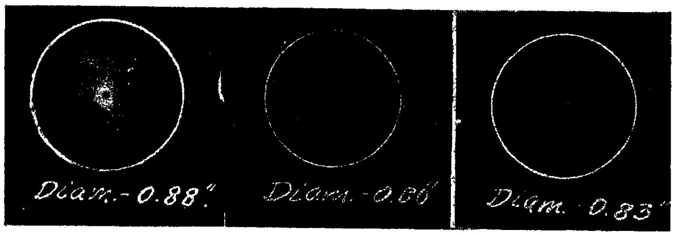
Typical results of tests are given in Figs. 1 to 4. The following table gives a summary of the complete results:

	Figure diameters for various loads and voltages			
Voltage kv. load	Bus	Bus + 20 ft. No. 22 wire	Bus + 2 — 15 ft. cables +20 ft. No. 22 wire	Mean
60	0.80 in.		0.88 in.	0.84 in.
63		0.83 in.		0.83 in.
80	1.14 in.	1.09 in.	1.12 in.	1.12 in.
100	1.24 in. 1.28 in.	1.23 in.		1.25 in.
125	1.51 in.	1.48 in.		1.495 in.

These results as a whole show no definite increase in figure diameter with corona. The deviation from a mean has been calculated for each voltage and was a maximum at the 60 and 80 kv. points, where it amounted to 0.04 in. and 0.03 in. respectively, or 3 kv.

If the very considerable amount of corona used in these tests had no appreciable effect on the voltage, it is to be presumed that the shortened cable lives noted by the authors must be due to some kind of resonance effect.

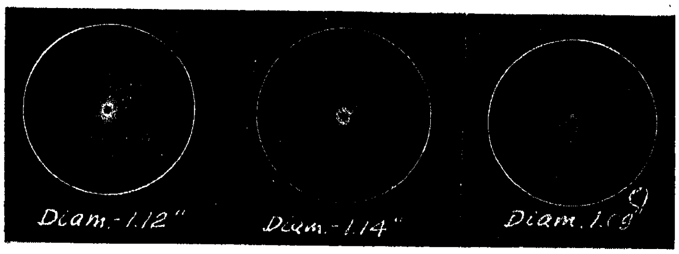
The authors carried all of their life tests to a point of breakdown. This was our practise until the last few months, when we changed to that of stopping the test when the sheath attained a certain temperature. This was ascertained by coating the sheath with wax containing red lead to give it greater visibility. When the melting point of the wax, approximately 60 deg. cent., was attained, the test was discontinued. This enabled us to catch incipient failures in the majority of cases. The paper tapes from such hot spots were removed from the cable and laid out on a board so that they could be studied with ease. One of the results of this study was to find that there are apparently two types of failure which may or may not correspond with the two types described by the authors. We designated these types as the radial and tangential type, respectively. In the radial type of failure, there was a direct puncture through the insulation without formation of dendrites. All tangential failures are radial in their final phase.



A B C

Fig. 1—Tests at 60,000 Volts

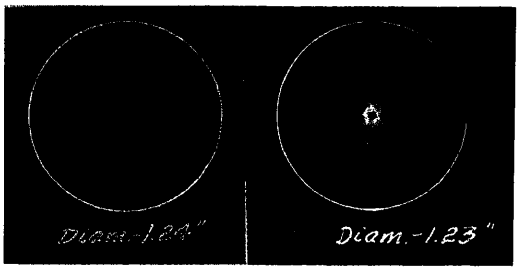
(*A*) Transformer loaded with bus and two cables
(*B*) Transformer loaded with bus only
(*C*) Transformer loaded with bus and corona-forming wire



A B C

Fig. 2—Tests at 80,000 Volts

(*A*) Transformer loaded with bus and two cables
(*B*) Transformer loaded with bus only
(*C*) Transformer loaded with bus and corona forming wire



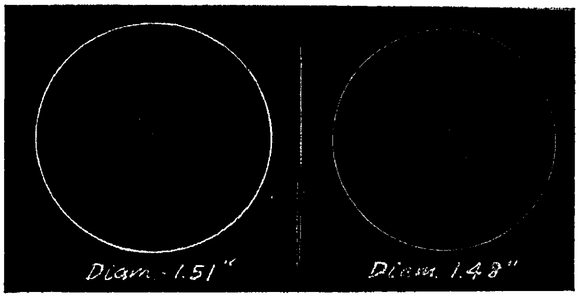
A B

Fig. 3—Tests at 100,000 Volts

(*A*) Transformer loaded with bus only
(*B*) Transformer loaded with bus and corona forming wire

The radial failures generally occurred without heating the cable sufficiently to melt the indicating wax, although in one case a partial radial failure was noted, which had not pierced the insulation. In the tangential type dendrites formed on the inner layers of the insulation. In all cases but one the dendrites were on the concave side of the tapes. The only case of a dendrite on the convex side of the tape (except where they were printed by the carbonaceous matter from the concave side of the adjacent tape) was found in a capacity-graded cable, where the hot spot and dendrites developed a little way in from the sheath. In this case the failure progressed from sheath to conductor and all the dendrites were on the convex side.

Dendrites originate opposite channels between tape edges. In the beginning they are isolated spatters of charred oil, but later they link together forming tree patterns which eventually burn into the paper. Each original spatter appears to be preceded by *X* formation and the *X* subsequently carbonizes. It is fairly well established that *X* is the result of ionic or short-wave bombardment of oil. Hence we may infer that the formation of dendrites is preceded by an ionic or short-wave emission from craters in the channels between tape edges.



A B

Fig. 4—Tests at 125,000 Volts

(*A*) Transformer loaded with bus only
(*B*) Transformer loaded with bus and corona forming wire

These observations show that the failure of impregnated paper insulation is a progressive event with a definite direction of travel, but they do not reveal the reason for any particular direction.

The authors state that "the specimens that were short-lived showed, upon examination, evidence of large quantities of entrapped air or gas and incomplete impregnation, as was indiindicated by dryness of the paper tape." It might be inferred from this that the authors regard this entrapped air or gas as the cause of the short life. Without entering upon the question of whether entrapped air does or does not cause short life, we found very strong evidence that cables may have very short life without any considerable amount of entrapped air, the gas which is found at the hot spot being generated by the latter and not being the cause of it.

The temperatures attained at the craters where hot spots originate are above the temperature at which impregnating compounds are converted into gas. Gas which is found in the cable in the neighborhood of a dendritic hot spot consists principally of hydrocarbon gas and not entrapped air.

If tangential type failures originate in craters between tape edges and do not depend upon the pressure of air, what causes them to form? An excellent working theory is that each crater is a miniature wave or electron-emitting vacuum tube. When the oil in a cable contracts in cooling, it will form vacuous bubbles in the channels if of high viscosity, but will draw oil from a considerable distance if of low viscosity. The dividing line appears to be a viscosity of about 20 minutes Saybolt.

In this connection it is significant that we have been unable to form dendrites in cable impregnated with thin oil (the so-called oil-filled type) even when purposely impregnated very poorly. Such cables, on life test, become hot throughout their length, without developing dendrites. The principal reason for the excellent time-voltage characteristics of oil-filled cable is the absence of dendritic hot spots and this, according to my theory, is due to the absence of minute vacuous bubbles and not to the absence of air.

The authors state in their conclusions that low pressures of evacuation are more important for the further withdrawal of moisture than for the reduction of air content. This is undoubtedly true of the samples having insulation walls of 65 mils. If the thickness of insulation had been ten times as great, say 650 mils, they might have reached a different conclusion.

The principal part of the author's work constitutes a very valuable contribution to our knowledge of the subject. All of the work has been done with such a high degree of experimental skill that the three papers in which it is described will long serve as a reservoir of facts, whatever interpretation may later be placed upon them.

John H. Palmer: Life tests on experimental cables have been in progress on cables with 220 mils of paper insulation and 80,000 volts between conductor and sheath. Considerable difficulty was experienced in testing these samples, due to the fact that ordinary commercial terminals failed to hold the voltage for any appreciable length of time. Several designs of terminals were tried, following an idea of Mr. C. F. Hanson, involving a graded condenser. The terminator as now used is based on a design involving a potential gradient not exceeding 5 volts per mil.

In order to attain a uniform potential gradient along any part of the insulation, it should be shielded with a metal shield, of diameter increasing with the distance from the lead, according to the following law:

$$D = \text{anti-log}\left[\frac{P}{\dfrac{E}{g\,l} - 1} + Q\right]$$

Where

D = diameter of shield (in.) at distance l (in.) from edge of sheath.
E = kv. conductor to sheath.
g = potential gradient, kv. per in. allowed along surface of paper.

$$P = \frac{K_t}{K_p} \log \frac{d_p}{d_c}.$$

$Q = \log d_p$.
d_p = diameter over cable paper, in.
d_c = diameter of conductor, in.
k_t = Specific inductive capacity of built-up tape.
k_p = Specific inductive capacity of cable insulation.

Example: One-conductor 500,000 cir. mil, 220 mils of paper, to be tested at 80 kv., let us assume

$$\frac{K_t}{K_p} = 1.1$$

$$P = 1.1 \log \frac{1.254}{0.814} = 0.207$$

$$Q = \log \quad 1.254 = 0.0983$$

l	$g\,l$	$\frac{E}{g\,l}$	$\frac{E}{g\,l} - 1$	$\frac{P}{\text{last}}$	Q + last	D anti-log last
0	0	∞	∞	0	0.0983	1.254
1	5	16	15	0.0138	0.1121	1.295
2	10	8	7	0.0296	0.1279	1.342
3	15	5.33	4.33	0.0479	0.1462	1.400
4	20	4.0	3.0	0.069	0.1673	1.470
5	25	3.2	2.2	0.094	0.1923	1.557
6	30	2.67	1.67	0.124	0.2223	1.671

The procedure is to build up to the diameter D with bias cut varnished cambric tape. After the 6 in. of base for the shield have been applied, the tape is built up as steeply as it can be laid for 1½ in. and then tapered in to the end of the cable. The object of the steep taper is to make a bulge beyond the end of the shield as a barrier against flashover. Heavy oil is applied between the layers of varnished cambric. The shield consists of lead foil or copper braid, applied tightly over the varnished cambric for 6 in., *i. e.*, up to the beginning of the bulge. The cable end thus prepared is inserted in a porcelain terminator.

F. M. Clark: The following discussion of the paper by Messrs. Whitehead and Hamburger includes several suggestions presented for consideration.

In drawing conclusions concerning the dielectric behavior of oil-treated insulation, it is necessary that the conclusions be limited to the type of specimen investigated. In the work done at Pittsfield we usually use a flat section of insulation between parallel aluminum electrodes built up to the desired electrical capacity. In some cases the electrodes may be wound cylindrically and later flat pressed to a form resembling a standard commercial capacitor. Our work is based entirely on Kraft and linen paper.

It has been found that in any study of the time voltage relation for fibrous insulation, it is a dangerous procedure to compute low-voltage breakdown from data obtained with breakdown over periods of only a few days or weeks. Experience has been that breakdowns in the laboratory are preceded in every case by corona formation. The factors governing such corona breakdown appear to be coupled with chemical changes in the dielectric solid or dielectric liquid. These changes are largely a function of heat concentration in spots and this in turn owes its source to the value of voltage used. In many cases the absolute value of voltage appears to be of more importance than the voltage stress. The procedure of calculating a breakdown for 2,000 or 3,000 hours from breakdown involving only a few days appears to present to us many obstacles with the limited knowledge at present available.

A rising power factor during the first few days of voltage application has been noted in insulation study at Pittsfield. In all work we have used a voltage as high as 825 volts per mil for dielectric thicknesses up to 8 mils. The life of the insulation may run over a period of several years. In practically every case, this initial increase in power factor is gradually lost and ultimately the original or even a lower power factor is obtained. These tests are carried out in sealed containers. The power factor rise during the initial stages of a life test has not been able to be associated with the total life of the insulation with any degree of reliability. The authors conclude that cable compound will deteriorate even if it is sealed in contact with air. This is a conclusion of considerable value. It should be carefully checked.

In Pittsfield a single stock sample of impregnating liquid of medium viscosity has been used for several years and no deterioration of liquid has been noted either in its chemical, physical or electrical properties, its electrical stability under aging test, or in the electrical characteristics of insulation treated with it. The liquid, however, is protected from the action of light although it is in a standard oil drum, with no special precautions aside from the usual oil drum seal. I assume that in the work presented by the authors, the treating compound is protected from light.

We can well agree with the conclusions of the present paper that the life of impregnated paper insulation increases steadily with a decrease in the amount of residual air. However, we would restrict this conclusion to experiments of a similar type to those performed by the authors. The effect of residual air in our tests becomes apparent only as the voltage of the test is raised well above those usually met in commercial operation. The effect of residual air appears to be coupled again with corona formation or chemical effects produced in the oil or paper which are strongly accelerated by the higher voltages in the presence of residual air. With low voltage operation, similar to those met in commercial practise, we have found no effect of residual air within the dielectric unless the air be contained in pockets, under which condition of course ionization and early breakdown become possible.

I desire to emphasize the importance of conclusion No. 8 which calls attention to the desirability of carefully controlling both the paper and oil used for electrical insulation. In our tests, we have found that most paper and oil shipments made exactly to the same physical characteristics, from the same source, using the same manufacturing method, and the same basic material may vary widely from shipment to shipment and the variation be of such magnitude as to affect seriously the electrical properties of apparatus involving their use. At the present time much expense is necessarily encountered by the designer of electrical apparatus in order to protect himself from such variations.

J. B. Whitehead: The increases in voltage rating and in carrying capacity and other characteristics of the oil-filled cable have led to the general feeling that it possesses inherently great advantages over cable of earlier, or as described by Mr. Roper, of "ordinary" type. While he does not make a specific statement, Mr. Roper nevertheless reflects a definite feeling to this effect in his comparison of the ordinary and the oil-filled types of cable, notably in his discussion of their relative stability, as indicated from their power factor characteristics, as well as in the obvious hope expressed in one or two places that the oil-filled principle may be extended to a wider economic range of voltage and load rating.

The question arises, therefore, as to whether Mr. Roper has made allowance for a superiority of this character in making his estimate of the relative capital costs and annual charges. Among his assumptions there is no evidence, for example, that any increase in stability or in life is allowed to the oil-filled cables. In item (20) the fixed charges, which presumably include depreciation, are placed at the same figure for all types of cable. In his conclusion (8) and in the results of Table II, Mr. Roper suggests that a moderate reduction in the cost of 66-kv. oil-filled single-conductor cable would cause it to show up much better in comparison with the ordinary type on the basis of economy. I should like to ask Mr. Roper whether a credit for increased stability and life of the oil-filled type might not swing the comparison of the 66-kv. single-conductor cable more definitely to the oil-filled type and perhaps even extend the economic oil-filled range even lower in the scale of load and voltage values.

Referring to Fig 31, it is surprising to find that in the original condition every one of these cables shows a rising power factor—voltage characteristic. This is very disconcerting because one of the principal advantages claimed for this type of cable is improved impregnation and avoidance of this condition. Referring to the improvement of these ionization characteristics with time, as shown in Fig. 31, we have frequently noted this type of change in our laboratory studies of the influence of residual air. In our experiments, however, it indicates usually a relatively poor condition of impregnation and relatively short life, as shown in Fig. 4 of our paper.

Referring to the same question, we have also noticed another type of slow improvement of power factor with time under test, which we have attributed to a slow improvement in the degree of impregnation. This type of change, however, is associated with perfectly flat original and subsequent power factor—voltage curves.

Based on the results of our laboratory studies, therefore, it is my feeling that efforts should be made to obtain flat power factor—voltage curves originally, rather than to rely on the tendency for an original rising characteristic to change to a flat one in the course of time.

R. W. Atkinson: Mr. Holmes has made available for use in the study of cable insulation the laws of probability. He has pointed out and emphasized the importance of the coefficient of variability, S, and has shown how its effect may be determined if sufficient information is available to obtain its value. The above points constitute the important part of Mr. Holmes' paper and these points should be very useful in the study of insulation. Having developed his theory the author then goes on to show how to apply it to practical cases. The writer wishes to emphasize the limitations of the author's method of attack on these practical cases and to point out certain errors in his assumptions.

The author attempts to show how to apply the developed theory to cable operation. He takes certain data which are based on five-minute tests but usually evaluated by means of an arbitrary exponent to a one-hour basis. He then re-evaluates these breakdown values in the same way to a 100-hour basis and assumes further that he can also evaluate it to one year, still on the strength of the five-minute results. Having done all of this extrapolation he applies his mathematics and tells us how much cable probably will fail in a given length of time at a given voltage. He suggests that at some later date cable engineers will determine the correct exponent, apparently failing to recognize the fact that the straight exponential relation between voltage and time applies only for small time differences, if at all, and that there is probably a more important variation, from one cable to another, with respect to this exponent than there is in the property which he is studying. The practical application thus given is, to say the least, definitely misleading.

The application of the developed theory should properly have been confined to the same terms as the observed data. It could then be pointed out how the probabilities so determined could be applied to longer periods if the voltage-time relation were known. For example, if the data from which the coefficient of variability is determined consist of five-minute tests, the method described in the paper would permit us to tell how many failures we could expect in five-minutes if say 100 miles of cable were tested at a given voltage.

The author points out that from 10 to 20 tests are necessary in order to determine the coefficient of variability. I wish to emphasize this point and call attention to the fact that in actual cases in any given lot of commercial cable it is very seldom that sufficient data are obtained to give a fair average, let alone the coefficient of variability. Even in the case of an order of cable large enough to furnish sufficient tests, the cable will be manufactured over a considerable length of time and might introduce a number of variables which would not exist if the cable were made at approximately the same time. The cost of making an adequate number of tests for the determination of variability would ordinarily preclude the possibility of their being made on any given lot of cable.

It should also be borne in mind that even 10 to 20 tests would give the coefficient of variability only for the range in the vicinity of the average breakdown value. If, for example, 10 tests are made, the ordinates must necessarily be in 10 per cent intervals with the lowest point at 5 per cent and the highest 95 per cent. Extrapolation must be resorted to below the 5 per cent value and above the 95 per cent value. Normally, in determining probabilities of failure in operation we would be concerned with probabilities much lower than 5 per cent. As the actual distribution function approximates the normal law only in the neighborhood of average values, extrapolation can not be expected to give accurate results either in the neighborhood of 0 per cent or 100 per cent. The author recognizes this in his Fig. 4 by plotting points above 80 per cent probability so that they do not follow the curve drawn. One danger of too much extrapolation is indicated in the author's statement under "Experimental Considerations" in the last part of section a. He states that with a coefficient of variability of 6 per cent we will obtain one failure per 100 miles of cable under a stress of 75 per cent of average while with a variability of 20 per cent the same result will be obtained with a stress of only 17 per cent of average. Following out the same mathematics it will also appear that in the case of insulation with 6 per cent coefficient a stress of 125 per cent of average will cause failures in all the cable except one section out of 100 miles while with the 20 per cent coefficient it would appear that we would be able to go to 183 per cent of average stress before the same result is obtained. In other words, the calculation would indicate that the poorer insulation would stand far greater excess stress than the better insulation.

Routine voltage tests made in conformity with cable purchasers' specifications might give important data as to the lower portion of the probability curve were it not for the inconsiderateness of cable manufacturers in making cable so good that it almost never breaks down under ordinary test voltage. By increasing the test voltage sufficiently, some failures could no doubt be obtained, but such a procedure is undesirable both on account of the cost of broken down cable and because of the possible reduction in the life of the remainder of the cable. Some years ago the writer advocated the practise of testing a certain portion of all high-voltage cables at a considerably higher voltage than specified. This practise was adopted three years ago by the A.E.I.C. and now forms a part of that association's cable specifications. Even where these tests do not result in failures, the data may be used in determining a limiting position of the lower part of the probability curve.

It should be recognized that the variability of insulation is more important than the average strength as determined by tests on all or a large fraction of the cable. As has been stated, financial considerations will prevent the destruction of an appreciable amount of cable for the purpose of obtaining the required data for the reliable determination of this coefficient. Attempts are being made by various people to develop a satisfactory procedure for its determination by tests on the entire quantity of cable without destroying any of it. One of the methods being tried, for example, is the discharge or noise bridge.

Cable specifications as now used constitute an attempt to measure insulation variability, but do this very imperfectly. Incidentally, it may be remarked that we are here concerned only with such properties of cable insulation as directly determine the ability of cable to withstand operating conditions. We should not confuse ourselves with a mass of information as to properties unimportant in this connection, the chief reason for the determination of some of which is often only the facility of measurement. Manufacturers' control, inspection, and testing will always be one of the prime factors in giving at least one of the limits of the probability curve. The determination must, however, always be based not on tests of a fraction of a per cent but on tests covering all or a major fraction of the cable.

H. G. Burd: From time to time criticism has been directed at the cable manufacturers for failure to improve their product rapidly enough. The rapid development in simplification of design and resultant economics in oil-filled cable and accessories does credit to the engineers of both the cable makers and the utilities. It also invites a parallel improvement in solid type of insulation. Some engineers are urging a reduction in thickness of insulation for medium voltage cable, as well as for high-voltage cable. Careful study is being given to this feature. Obviously, mechanical considerations affect the minimum walls of insulation permissible. Also, a cable that may be workable on one system may not necessarily be equally successful on a second system. For example, a steady heavy load is less damaging to cable operation than an extremely variable load with wide temperature variations.

Parallel improvement in solid type cable is already noticeable. The research programs started several years ago were planned to develop fundamental conclusions regarding insulation. Professor Dawes of Harvard reported that all occluded air, gas, and moisture could be removed from oil if broken up into thin layers under practically absolute vacuum. Power-factor voltage curves with flat characteristics up to 300 volts per mil were obtained for compounds thus treated. These results held good almost regardless of the type of compound which proved definitely that air, gas, and moisture were the chief causes of trouble. Davis and Eddy indicated that oil at atmospheric pressure will absorb air up to 10 or 15 per cent of its volume. This work connects Professor Dawes' results closely with the work of Emanuelli, Shanklin and Mackay and shows clearly that ionization would increase in direct proportion to the void volume in the cable. Therefore, if ionization is to be prevented, every precaution needs to be exercised to remove air and moisture completely.

The study by Messrs. Whitehead and Hamburger at Johns Hopkins has been directed toward residual air and moisture in impregnated paper insulation. After dealing, in earlier studies, with fairly high pressure of evacuation and impregnation, and a repeated preliminary statement in this paper to the effect that a pressure below 2.5 cm. Hg. is not necessary, we now find that for the studies in paper No. 3 they report (on page 1431) drying of the core under ½ mm. Hg. and spraying of the oil (to break it up) into a chamber evacuated to a pressure of ½ mm. Hg. Finally, keeping the oil under this degree of vacuum.

It is exceedingly gratifying to us to note the use of this extremely high vacuum, for two years ago we had opportunity to build and equip a new mill for cable manufacture and were, naturally, extremely anxious to incorporate in it all the benefits of the latest research developments. Commercial adaptation of these important laboratory advancements was the extremely difficult problem which confronted us. We also made numerous tests on commercial lengths of cable under the vacua available in old impregnating tanks, then with these same tanks improved to hold much lower pressures, namely, higher vacua. And this showed the difference dealing with full lengths of cable, with various degrees of vacua.

The inference seems quite clear from their second and third papers that it is not necessary to go to 1 or 2 mm. Hg. impregnation or oil pressure treatment to secure the best finished cable product. Our disagreement with them is in the same channel as 1928 discussions of the second paper by Messrs. Mackay and Del Mar.[2] The major difference is in university laboratory *vs.* commercial cable mill manufacturing methods. It is quite one thing to handle small amounts of material in miniature apparatus and with miniature samples, and vastly different to treat large masses of strand, paper and compound, bent around a drum, in a cable factory. There we are also dealing with cable from 65 mils wall thickness up to 750 mils. Obviously, to obtain the same results as in a laboratory, large masses would need a higher degree of vacuum.

Even the various results in the laboratory on samples as reported in this latest paper are quite erratic. The conclusions, themselves, on page 1439 are certainly an excellent brief for high vacuum treatment. Finally note that oil-filled cable, with its lesser walls of insulation and perfect operating record, is so treated.

In conclusion No. 5 and other places, reference is made to long life and the inference may too readily be taken that this means long operating cable life in service. The two are vastly different, in fact it should be clearly kept in mind that these are simply extremely high-voltage life tests, and on samples. Solid type cables operate at from 30 to 50 volts per mil average stress. Testing at 300 volts per mil and higher can hardly be a completely satisfactory accelerated life test. While continuing to test that way because it is the present specification requirements, in the past several months we have been giving attention to methods which would more nearly simulate the operating conditions of cable in service. We have run cyclic loading tests on both belted and shielded type of cable and also have carried cable through repeated temperature cycles without loading but by oven heating and cooling. Two or three years ago the Detroit Edison and Brooklyn Edison companies tried cyclic loading tests but apparently with results not completely satisfactory. These tests have also been tried abroad. Our tests have been made with much planning and care and have been very gratifying and satisfactory.

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[2] Trans. A.I.E.E., July 1928, pp. 839-840.

We do not propose cyclic loading tests as a satisfactory substitute for the present methods of factory acceptance testing of cable. Obviously, these tests take too much time and are too costly. But it is a significant coincidence that cable made this way and so tested has parallel operating life in service to oil-filled cable.

These two types of test also take the cable to much higher temperatures than the 40-50 deg. cent. mentioned in the papers by Messrs. Whitehead and Hamburger. We feel it is most important to cover this temperature range in an attempt to judge good cable from bad.

Every experience that we had in the past year indicates that while extremely high vacua and separate treatment of sprayed oil and core, keeping the air at all times away, is a more expensive method of cable treatment, its use, combined with continued improvement in the (now quoting from page 1439 of Messrs. Whitehead and Hamburger's paper) "uncontrolled variations in the uniformity and quality of oil and paper," clearly offers a method whereby vastly improved solid type of insulation is secured, paralleling (as mentioned in the first part of this discussion) for solid type of insulation the improvements in oil-filled cable.

E. G. Linder: The influence of the small amounts of moisture and air which reside in the impregnated paper insulation of cables immediately after their manufacture, has been discussed by Messrs. Whitehead and Hamburger, but no mention has been made of the moisture and gases which may be produced in the cable after its installation. The residual moisture and air may serve to initiate the deterioration, but it seems that the reaction products generated by the glow discharges in the voids must play the most important part in the subsequent course of the deterioration.

During the past few years we have been studying at Cornell University, the reactions of organic compounds in the glow discharge, for the purpose of throwing light on the process of decay of cable insulation. The Cornell studies, while specialized and purely scientific in nature, are supplementary to a more general and practical program of cable research being carried out by the Detroit Edison Company.

In spite of the fact that it is now generally believed that ionization in discharges in voids is the principal cause of cable deterioration, a surprisingly small amount of research has been done on the chemical effects of these discharges. In fact, it seems that the Detroit Edison Company's work, together with the supplementary work at Cornell, is the only investigation which has been made along this line. The field is certainly of sufficient importance and breadth to deserve the attention of a much larger number of investigators.

Our work has thus far dealt mainly with the effects of discharges in pure hydrocarbons, rather than in mineral oils, which are usually mixtures of some two hundred different hydrocarbons and therefore too complicated chemically to be suitable for a scientific study aimed at determining the fundamental processes.

About seventy different hydrocarbons, including representatives of all different types, have been investigated, and it has been found that they all react in the glow discharge (without the presence of air or moisture). The discharges have been produced in the vapor phase of the hydrocarbons, as they would occur in the gases in the voids in cables. Solid, liquid, and gaseous products have been found to be produced, in apparently complicated mixtures consisting of many different compounds. The solids are partly waxy, amorphous substances, and partly crystalline. The liquids seem to range from thick, syrupy compounds, to light, volatile ones. However, as yet, only a very meager study of the solids and liquids has been made, and there are but few reliable data as to their nature, the investigation having been largely confined to the gases.

The chemical composition of the gases from the different hydrocarbons does not vary over a wide range. It is about the same for aromatics as for paraffins, and consists of from 40 to 60 per cent hydrogen, 50 to 30 per cent unsaturated gases, and about 10 per cent paraffins. This composition does not correspond with that of gases found in actual cables, which run about 90 per cent hydrogen, but correspondence should not be expected since we are here studying the primary reactions in simple pure hydrocarbons, and not the more complicated series of reactions in complex oils which actually occur in cables. Extensions in that direction logically come later on after the fundamentals have been made clearer.

Under arbitrarily standardized test conditions, it has been found that paraffins produced three or four times as much gas as aromatics, but on the other hand, aromatics produce two or three times as much insoluble wax. The gas-to-wax ratio by weight for aromatics is about 3:1, whereas that for paraffins is about 50:1. There appears to be a rough relation between the degree of saturation and the amount of wax produced, the rate of wax production increasing with decreasing saturation.

Definite relationships between the rate of gas production and molecular structure have been found. The results appear to be in harmony with two rules, namely;

(1) In a series of similar compounds, the rate of production of gas increases with the molecular size.

(2) In a series of similar compounds (all of the same molecular weight) the rate of production of gas decreases with increasing molecular centralization.

As an example of rule (1) the n-paraffin series may be cited, the rate of gas production increasing with the length of the carbon chain; as an example of rule (2) the series, n-butylbenzene, sec-butylbenzene, and tert-butylbenzene, may be given, the rate of gas production decreasing in the order in which the compounds are listed.

We have shown, therefore, that even in the absence of air and moisture, complicated chemical reactions occur in hydrocarbons, which must play an important part in cable deterioration. It is planned to start an investigation immediately on oxygen-containing compounds, such as alcohols, esters and ethers, with the purpose of throwing light on the effect of the presence of cellulose in cables. It is anticipated that the presence of oxygen, along with the carbon and hydrogen in the compounds, will result in the actual formation of large amounts of water.

Some of the above results have been published in the *Physical Review*, 35, 1930, p. 1375. Further data will soon be available in detail in a number of forthcoming papers in scientific journals.

Edwin B. Middleton: In the paper by Messrs. Shanklin and Buller under "Advantages," a statement appears "Positive oil pressure is maintained and because of this, flaws and defects in the lead sheath merely result in slow leakage of oil which can be located and repaired at any convenient time. Electrical service failure caused by entrance of moisture and air is usually the first warning of such defects in solid cable." Also, under "Other Factors and Characteristics—Strength of Lead

Sheath," there is this statement, "The integrity of the sheath is a very important feature of oil-filled cable practise."

Electric power cables for high-tension service consist essentially of a conductor and insulating layer, usually impregnated paper, and an extruded lead sheath. Conductors are universally satisfactory and oil impregnated paper insulation has reached a high state of perfection due to continued study by manufacturers and operators. However, the lead sheath extrusion process has changed but little and is essentially the same as 30 years ago. It is believed that more accurate methods should be developed for the control of the lead covering processes. These should include not only control of the temperature of the material, but also freedom of the molten lead from accumulations of foreign materials that might affect the integrity of the finished product.

After approximately two years use of positive pressure reservoirs in connection with 66-kv. solid type single-conductor cable in the Philadelphia Electric Company system, I feel that the integrity of the lead sheath is equally as important in the case of the solid insulation type of cable as with the oil filled, and for the same reasons in each case. Since replacing the original sylphon installations with positive pressure reservoirs, it has been necessary to withdraw a number of cable sections due to split sheath. These situations were detected by oil leaking from the duct mouth.

An analysis of these troubles seems to indicate that a large proportion of these sheath failures are undoubtedly the result of inherent manufacturing defects. By their nature they could not be readily disclosed by tests. It appears, therefore, that these defects only become apparent as the result of many repeated movements of the cable closely following the load cycle, combined with the pressures imposed by the reservoirs. The former factor was probably a very large contributor to the ultimate failure since laboratory tests on cable samples at sustained pressures well above those which it is reasonable to believe exist in service, did not disclose discernible changes in the sheath.

There also appears in the Shanklin and Buller paper, under "Other Systems of Oil Feed," the statement "Segregation where actually required can be obtained by safer and more economical means." This refers to what the authors might call the elimination of unnecessary stop joints. I would like to learn just how the authors propose to eliminate or minimize the present form of stop joint and still secure adequate segregation.

Howard S. Phelps: Referring to Fig. 3 of the paper by Messrs. Atkinson and Simmons, there is an operating problem to which attention should be called. The authors make no mention of studies they may have made of materials other than galvanized steel for the outer casings of the oil reservoirs. It would seem, however, serious consideration should be given this feature of the system they propose.

Observations in Philadelphia of both aerial and underground transformers housed in steel tanks, even the so-called copper-bearing steels, have led to investigations of corrosion resistant materials and finishes that might be used advantageously for transformer tanks and similar applications in underground construction.

The condition of some 150 samples, after approximately 18 months' installation in manholes of the Philadelphia Electric Company's underground transmission system indicates that for sheet materials, such as used in the outer shell of the oil reservoir, there are but few commercially available that may be expected to have a life anything like approaching that which is expected of lead-sheathed cable.

It would be reasonable to presume that the outer shell of the pressure type variable volume oil reservoir would require a number of welding operations in its manufacture. It has also been found, and the Philadelphia tests confirm the point, that even the "stainless steels" have very poor resistance to corrosion in the event that any welding processes have been applied to them.

In lieu of using materials concerning which there may be questions as to their ability to resist corrosion, but which are used because of lesser cost, it might be found economically advantageous to use other materials concerning which there is little, if any, question of ability to withstand corrosion and thus obviate routine inspections of equipment at intervals of two or three years to determine if corrosion has set in, together with a program of protective painting should corrosion be found.

T. N. Riley: Direct-current control of drying makes it difficult to obtain comparative and reproducible results with any high degree of accuracy. If a short time reading is taken the conductivity is rapidly changing owing to the absorption effect, and if a long time reading is taken the real conductivity of fibrous hygroscopic materials is liable to be obscured by polarization effects. We have preferred to make control measurements of a-c. leakance and conductivity at 800 cycles alternating current because at this frequency the power-factor temperature curve is not so steep as at 50 cycles and small temperature errors are less likely to obscure any changes in power factor due to other causes. This seems to me particularly important in dealing with papers of quite different characteristics as in the tests reported in the paper by Messrs. Whitehead and Hamburger.

Arising out of this difference of paper supplies I think too much weight is attached to porosity tests alone. It would be quite possible to get two totally different papers with equal porosities one having, for example, few relatively large spaces between fibers and the other a large number of relatively small spaces giving equal air flow on test. Assuming an equal condition of the fiber surface the latter would probably take up oil more rapidly owing to a greater capillary pull. The fiber surfaces themselves may differ widely according to the beating received in manufacture. The No. 2 paper, for example, appears to have been highly beaten resulting in a considerably greater hydration of the cellulose than occurred in Nos. 1 or 3. The conductivity is therefore intrinsically greater, since a large part of the water is chemically combined and cannot be removed without breaking up the paper structure. Such excessive beating would tend to give a paper of lighter weight for a given thickness, particularly if the porosity is high. It seems to me therefore that to obtain comparative results, paper of known and uniform absorbency, density and porosity must be used.

It appears quite possible that the increase in power factor with increase of voltage shown, for example, in Fig. 6 may really be due to a local rise of temperature in the insulation caused by the increased loss at the higher stress (which temperature control of the oil bath could hardly prevent) and is not a voltage change at all. I am the more inclined to this view since the change appears to be slow and to take two hours or so to establish, whereas a change really due to voltage would probably take place very quickly.

The next point is that the small differences obtained in life for impregnation at pressures between 2 mm. and 2.5 cm. are probably due largely to the conditions of the test, that is to say that when the thinly insulated sample is exposed to oil penetration along the whole length, the oil, whatever its condition after impregnation rapidly takes up gas from the oil bath exposed to nitrogen at atmospheric pressure. The result of the low-pressure treatment is therefore largely nullified. A tighter structure would slow down oil movements and by retarding the re-gassification give longer life as is reported.

With 40-cm. impregnation on the other hand there is a tendency for an opposite effect, *i. e.*, for oil penetration into the body of the paper to continue slowly while the cable is in the bath, the improvement in filling counterbalancing any increased gassification of the oil. There seems good reason to believe that the real differences produced by impregnation at different pressures are greater than the test results indicate.

With actual high-voltage cables employing a much thicker insulation and having an impervious lead sheathing preventing easy access of gassified oil after impregnation, the improvement obtained by high vacuum impregnation would be much more marked.

With good impregnation and gas free oil there is no initial rise of power factor as shown in Fig. 7. Such rise is definite evidence of defective impregnation. It is therefore to be expected that longer life is obtained with a smaller initial rise of power factor, but it is somewhat surprising that any quantitative relationship should exist between the two factors such as is shown in Fig. 8. The erratic distribution of the single tests in Fig. 9 is more easily appreciated.

There is another effect occurring in actual cables which tests in an oil bath do not show up. Suppose a cable is impregnated in relatively poor vacuum and is then lead sheathed. A test immediately after manufacture may give a flat power factor—voltage characteristic. If now the cable is allowed to stand for a few weeks a repeat test may show a characteristic rising with voltage. The explanation probably is that in impregnation the separating layers between papers are first filled leaving the papers themselves isolated. Such trapped air or gaseous spaces as exist at first are largely in the body of the paper, and being finely divided, do not ionize under voltages up to values considerably above normal. On standing, however, the paper continues to take up compound at the expense of the layers between papers, in which case what gas there is tends to collect in larger aggregates. These spaces now ionize at a lower voltage so that the characteristic of the cable is changed on standing. If oil is available from a surrounding bath, it is not to be expected that this effect would show up so markedly. It may be, however, that the initial rise of power factor found is really due to this time factor alone and is not dependent on continuous application of voltage. It would be interesting to know whether any tests have been made which would clear up this point.

Robert J. Wiseman: Mr. Roper's paper is a very fine treatise on the economics of cable operation in comparing the oil-filled type of cable with the solid type of cable. It is true that a positive pressure must be maintained at all times on the oil-filled cable. I think it is equally true that we should have positive pressure on solid cable. With present day compounds used in solid cables, this is not obtainable at all times. Studies are now being made to determine how fluid an oil must be to accomplish this end. We are learning that other factors beside fluidity of an oil have an important bearing on the successful operation of a cable and that the use of a low viscosity oil in solid type cables may be undesirable. However, we have found by accelerated aging tests that solid type 132-kv. cable can be made to operate successfully.

It is interesting to note that the 1930 oil-filled cables used a lower viscosity oil than the 1927 cables. Mr. Roper gives this as the reason why the single lead sheath was used for the 1930 cables as compared to the double reinforced sheath of the 1927 cables. As the 1927 cables have not been loaded as high as permissible, they have not yet been subject to the effects of sudden changes in temperature due to changing load. I am more inclined to believe that the lead sheaths on the 1927 cables were too thin to start with and each by itself was not able to withstand the positive pressure necessary. If a single heavy lead sheath was used, they would not have experienced the sheath failures they did. It is believed also that equally as good operation can be obtained with a slightly heavier oil than even used in the 1927 cables and also obtain a more stable oil.

The paper by Messrs. Shanklin and Buller is a very interesting treatise on the theoretical aspects of oil-filled cable. Some of the advantages over the solid cable are being met by changes in types of oil and paper in the latter, but from tests which we have recently made, we are still not able to duplicate entirely the oil-filled cable, although the solid 132-kv. cable is a feasible design.

It is possible to obtain on solid type cable, power factor—voltage curves similar to those shown by Mr. Roper in Fig. 31. We have under test, a 132-kv. solid cable which has been subject to double voltage for over 500 hours and many load cycle tests up to 78 deg. cent. on the copper. The power factor is decreasing with time and compares favorably with the oil-filled cable. We are planning to increase the voltage to three times operating voltage in order to speed up the test. With our changing views on solid cable, it is possible that three-conductor, 66-kv. cable may be furnished in the near future.

We have found when studying the absorption of gases by oils that the more easily the oil is absorbed, the harder it is to extract the gas again. Carbon dioxide was very easily absorbed and hard to extract, whereas nitrogen would not be easily absorbed and very easy to extract. Air was intermediate between the two gases.

The paper by Messrs. Atkinson and Simmons opens up a new field of study and application of the principles of electrostatics to cable joints and potheads. I believe that the condenser type of joint will be adopted for all high-voltage, single-conductor cables and also three-conductor for 33 kv. and over. The advantages of reduction in length, the making of the unit in the factory, the reduction in the time of making of a joint in the field and, therefore, the time of exposure of the cable to the air are all important enough to consider for the future cable.

The difference in the results obtained by the two oils *A* and *B* in the Whitehead, Hamburger paper indicates what we have all found, namely, that the oils during the last year or so have been far superior to previous oils and it is not possible to make a direct comparison of results because of the changes in the characteristics of the oils.

The reduction in power factor which is shown in Fig. 7, Section 90-A has been found on some cables we have tested with current loading and overvoltage, our time extending over several hundred hours.

The influence of the type of cable paper on the electrical characteristics of the combination of oil and paper is most important. We have tested many samples of paper with the same oil and obtained widely varying results. The effect of porosity (air density) is quite important. Also, the weight density, fiber formation and manner in which the paper was made, that is, the boiling of the pulp, washing, beating, and manner of calendering.

The ideas advanced in the paper by Mr. Holmes would have possibilities if a large number of tests could be collected on the same cables to obtain the proper constants. However, each reel of cable manufactured is slightly different than all other reels and a group of cables of one manufacture will have different constants than cables of another manufacture. Considering the low number of high-voltage tests which are made on a given order (one short time test and one long time test, per 15,000 ft. of cable), there are not a great deal of test data to analyze. However, this should not deter us from trying to apply Mr. Holmes' ideas to our laboratory test data. As his predictions are based on the ratio of sigma to Ea, or coefficient of variability, the smaller sigma becomes, the more nearly we can operate a cable to its average breakdown stress Ea. To date, we have had quite a variation in sigma, due equally as much to end failures of the samples as variations of failures under the sheath, perhaps more so by end failures. It is true that higher and more uniform values of breakdown voltage are being obtained today, but further improvement is desirable and all of it cannot be obtained by improvements in cable manufacture; improvement in test methods is necessary.

Too much must not be expected from this method of predicting cable failures in service. Only about 20 to 25 per cent of all cable failures are chargeable as inherent cable defects. Therefore, we are only guessing as to the possibility of some of these failures. Also, our predictions are based on laboratory voltage tests. Cable failures are caused from the effects of the current load cycles a cable is subjected to in service. As the cable goes through the temperature effects due to current loading, the compound migrates due to the increase in its volume and pressure created. This movement can be both longitudinal and radial as the cable heats up. On cooling if the compound does not return to its original position in the cable, the uniformity of saturation is upset and we have the beginnings of the deterioration of a cable. It may take years for it to develop in service to a condition which is serious. The time as to when the cable will fail cannot be predicted ahead as the influencing factors—variation of current loading, suddenness of change and range of temperature from cold to hot to cold—vary from day to day.

The best that can be obtained from these new ideas is that considering the laboratory tests only, the cable having a low value of coefficient of variability may give a better account of itself than a cable having a high coefficient of variability. Note, however, that as the breakdown voltage goes up, a higher value of sigma for the same coefficients is permissible. Is this not a talking point for the highest breakdown voltage possible?

The law of probability appears to have been substantiated in this paper. The writer recalls studying the effect of size of electrode area on the breakdown voltage of varnished cambric about fifteen years ago. Tests were made with a single electrode and also with a large number of small electrodes to give the same area. In each case the same breakdown was obtained for the same total area. The law of probability did not apply. Instead it appeared that the effect of electrode area on the dielectric strength could be expressed as a function of the reciprocal of the square root of the radius of the electrode.

G. B. Shanklin: I fully agree with Dr. Whitehead's statement that a flat power factor—voltage characteristic is a very important criterion of cable quality. We have never accounted for the slightly rising characteristic in the test cable furnished Mr. Roper. Apparently, this particular cable is "the exception that proves the rule."

Mr. E. G. Linder rightfully points out that the chemical changes that occur when ionization exists have a very important bearing on cable life. We do not fully agree with him, however, in concluding that knowledge of this effect is even more important than ways and means of removing initial impurities. Ionization is merely a symptom or result of disease. Prevention of the disease (voids) is the correct treatment.

Mr. Middleton wishes to know how segregation of lengths of oil-filled cable can be obtained without resorting to stop joints. This is accomplished by use of simple semistop joints as described in a separate publication, *Gen. Elec. Review*, July, 1931.

Although Mr. R. J. Wiseman seems to agree with us regarding the relative merits of oil-filled cable for 132-kv. service, he also feels that solid cable is, or can be made feasible for 132-kv. service by using amongst other things, a comparatively thin impregnating compound. We have had a good deal of experience along these lines and agree, as far as improvement in endurance quality of solid cable is concerned, but our research and experience have never indicated that this improvement will carry solid cable into the 132 kv. class.

F. H. Buller: There are two points in the discussion by Messrs. Miller and Wollaston with which we are in whole-hearted agreement. First, the equations for the temperature transients and oil demand are decidedly cumbersome; and second, we are fully aware of the fact that the principle of superposition applies to this problem.

We cannot, however, accept the estimate of one week as the time required to obtain numerical results from our equations. Experience indicates that from one and one-half to two days are actually required. The most tedious part of the process is the evaluation of the root of equation (4), which feature is also essential to Mr. Miller's solution.

We wish to point out that a complete theoretical solution is always the first and most necessary step in the handling of any problem, even though it may be cumbersome. After such a solution is developed, it gives an exact understanding of the problem, and furnishes a basis for further progress in the way of simplifications and short cuts, the accuracy of which can be determined by comparison with the complete solution.

There are two methods of reaching a simplified short-cut solution of this particular problem. First, by the use of charts, as proposed by Messrs. Miller and Wollaston. Second, by the use of a mechanical model, as proposed and used by Emanueli. We are yet undecided as to which of these two methods will be adopted for future routine calculations. We would not be willing to adopt either of these approximate methods if the complete solution were not available as a final check and guide. A set of charts, such as Mr. Miller proposed for the rapid evaluation of the roots of equation (4) would be very useful indeed.

Since Messrs. Miller and Wollaston have drawn attention to the principle of superposition, it may be pointed out that it was used in deriving equation (2) for A_n; and that it can be used readily, in conjunction with our equations, to obtain the solution for loads varying in any manner whatever.

It is, of course, unnecessary to solve equation (2) for A_n for each change of load. A simple multiplication is all that is required, so long as copper loss, sheath loss, and dielectric loss maintain a constant ratio. Even if these ratios are not constant, the labor of solution is only increased very slightly.

One of the criticisms presented by Messrs. Miller and Wollaston concerns the manner in which the distribution of dielectric loss has been handled. In this connection, it would be well to note that one of the authors, working in collaboration with Mr. R. H. Park, to whom grateful acknowledgment is hereby made, developed a formula for A_n which takes into account with full precision almost any conceivable distribution of losses, dielectric or otherwise. This formula is more complicated than the one which appears in the present paper. It is, however, available, and can be used to check the oil demand and temperature transients whenever such a check is warranted. For most practical cases, however, the more simple formulas presented in our paper hold with good accuracy.

Messrs. Miller and Wollaston's method of evaluating the A_n coefficients is perfectly practical. It will give a close approximation to the right answer providing that all the preceding theoretical and numerical work has been correctly performed; but it is not self-checking. The solutions developed by the present writers involve the calculation of the coefficients without direct reference to the numerical values of the boundary condition mentioned by Messrs. Miller and Wollaston. When the coefficients have been thus evaluated, the resultant expression will be found to check this boundary condition closely, providing a sufficient number of terms is used, unless some numerical error has been made. The method is thus self-checking. Usually, three terms will give a result close enough for all practical purposes.

R. W. Atkinson: We have been very much gratified by the favorable reception of the condenser type joints and terminals. One or two points brought out may be developed a little further.

Mr. Shanklin, agreeing with the correctness of the condenser principle as applied to high-voltage joints and terminals, points out that, in competition with the non-condenser construction which has been proved by use, they must be shown by experience to be equal mechanically and electrically, and equal or lower in cost. This is, of course, entirely true, and considerable operating experience is now available to confirm very satisfactorily their mechanical and electrical reliability. It is believed that all of the expectations regarding these are well justified.

It has been customary to assume that a "feeder" joint (that is a joint at which the cable is connected to the oil supply) needs to be a "stop" joint, and this requirement has been the controlling factor in determining the number and location of stop joints in single-conductor lines having comparatively level contour. With the earlier types of stop joint and hand-wrapped normal joints this was necessary, but the condenser construction lends itself readily to use as a non-stop, feeder joint. When so used the stop tubes may be eliminated entirely, resulting in a joint much simpler than the hand-wrapped type, and an actually lower installation cost. This feature, combined with the reduction in manhole space required below that required by earlier designs of stop joint having comparable electrical strength, is of great importance in its effect on the overall cost of the installation.

In his discussion Mr. John H. Palmer gives the formula which he has used in determining the contour of metal shields for cable terminals.

In our paper the following formula is given for the determination of the slopes of electrodes in the cylindrical condenser joint:

$$r'' = r'\left(\frac{r'}{r}\right)^{\frac{v}{V-v}} \qquad (1)$$

in which r is the radius of the conductor
r' the radius over the conductor insulation
r'' the radius at a given point on the shield
V the cable voltage
and v the voltage at a point on surface of the conductor insulation radially below the given point on the shield.

If the added insulating material were different than that in the cable and if we represent by K_1 and K_2 the respective specific inductive capacities of the cable insulation and the joint insulation, the formula is as follows:

$$r'' = r'\left(\frac{r'}{r}\right)^{\frac{K_2}{K_1}\frac{v}{V-v}} \qquad (2)$$

The formula given by Mr. Palmer is mathematically identical with formula (2).

Lack of space in our paper caused us to limit our discussion of the formula to its use for terminations of condenser plates in cylindrical condenser joints. However, we have recognized that the formula is equally applicable to shields for terminals and have employed it for that purpose.

The above formula has the interesting property that the longitudinal stress along the surface of any cylinder concentric with the conductor is uniform. The value of this stress is different for each cylinder, increasing as the diameter of the cylinder increases, so that at the end of the shield the longitudinal stress may be considerably higher than at the beginning. We derived a formula for shields which gives uniform longitudinal stress along the shield. This formula is as follows:

$$r'' = r'\left(\frac{r'}{r}\right)^{\frac{K_2}{K_1}\left(e^{\frac{gl}{v}}-1\right)} \qquad (3)$$

in which g is the longitudinal stress at any point on the shield
l the distance from the edge of the sheath to the given point on the shield
e the base of Naperian logarithms

and the other symbols have the same significance as for (1) and (2).

In various applications we have found it of advantage to construct terminal shields in accordance with formula (3) rather than formula (2). The shields used by Whitehead and Hamburger, for which they gave credit in their paper to one of the authors, were designed in accordance with formula (3).

As was stated in our paper, the matter of using distributed capacity and shields so shaped as to relieve stress concentration has been given a great deal of thought by engineers throughout the world for some time. Various formulas have been derived by various people under certain assumed conditions. Under the same assumptions formulas derived by different engineers will, of course, be mathematically the same. For example, German Patent 383346 issued to the Pirelli Company in October 1923 mentions a formula for terminal shields which is mathematically identical with formula (3) when $K_1 = K_2$.

The importance of such mathematical analysis, and the utilization of means of control of potential distribution, such as is offered by the condenser construction, is progressively enhanced as operating and test voltages are still further increased. With earlier types of construction, the size and cost of joints and terminals bear an exponential relation to the electrical strength, so that at the highest operating voltages, any increase in voltage requires an enormously greater proportional increase in size. With the condenser construction, on the other hand, the necessary increase in dimensions is almost in direct proportion to the increase in electrical strength required. Whereas only a few years ago we seemed to have almost reached the economic limit in voltage for cable operation, the new developments which have here been discussed have again pushed the practical limit safely beyond the present demands. The remarkable operating record of 132-kv. oil-filled cables; the even more remarkable results of tests at high stresses; the actual making and testing of normal commercial lengths of cable adapted for operation at 220 kv.; and the development of accessories and of joints and terminals of the type described, make the use of cables at this voltage immediately practicable.

M. C. Holmes: Referring to Mr. Atkinson's discussion, it seemed obvious, but perhaps it should be stated explicitly, that the equations do not apply in the case of operating voltages higher than the mean breakdown voltage of the samples, so that arguments as to what they predict for operating voltages of 125 per cent are meaningless as well as trivial. If Mr. Atkinson understands a long-time test to mean one of five-minutes duration then he is justified in his criticism of the method of application. The author believes, however, that he has applied it in exactly the manner which Mr. Atkinson suggests.

Mr. Shanklin discusses the limitation of the theory on the ground that few if any failures in modern cable are due to causes inherent in the insulation. Mr. Wiseman objects to it for the same reason but states that only 20 to 25 per cent of all cable failures are chargeable as inherent defects. As a matter of fact, neither view is entirely correct. The facts are easily ascertainable. They are contained in the annual report for 1928 of the subcommittee on cable operation of the N.E.L.A. The results on the 10,000 miles of cable in the United States for the period 1923 to 1928 show 33 to 45 per cent of all failures to be attributable to "Inherent or Unknown" causes, and for the same period, 25 to 31 per cent "known to be due to causes inherent in the insulation."

In considering the applicability of the laws of probability to such problems as the present one it should be emphasized that while we cannot predict with any degree of certainty the results of a single test on a piece of cable, we can predict with certainty and exactness what will happen "in the long run" or "in the aggregate." The quantities dealt with in this paper should be considered from the same viewpoint. The laws of probability apply in the case of the chaotic motions of molecules, in determining gaseous pressures, as well as for the life insurance companies in predicting the behavior of aggregates of such variable units as human individuals. The subject is an extremely practical one as may be seen from a consideration of the many different fields in which it has been successfully applied.

Mr. Wiseman speaks of experiments made to determine the effect of electrode area on breakdown voltage and concludes that the law of probability did not apply. The author would be interested to know which one of the laws of probability did not apply, and by what chain of reasoning the conclusion was arrived at. It should also be obvious that end failures of samples and failures in pot-heads should not enter into the calculation of sigma.

In conclusion, it is felt that the main objectives of the paper should be restated. They are two-fold; first, to provide a measuring stick for gaging the hitherto vaguely expressed term, variability; and second, to show quantitatively, the part played by the variability in determining breakdown voltages.

D. W. Roper: It is very gratifying to have Mr. Shanklin's confirmation of my economic data on cable with the two types of insulation. Mr. Shanklin's comparison of the relative future prospect of the two types, however, assumes that no reduction will be made in the cost of cable with the ordinary type of insulation. If such is the case, the progress and experience abroad indicates that it will be because the American manufacturers have lost interest in the improvement in insulation of the ordinary type. In Chicago there have been only seven failures in 238 miles of 66-kv. cable that was shipped 1927-1930, inclusive, and in each case careful examination subsequent to failure indicated that the cause of the trouble was due to a local deficiency in impregnation. While such deficiencies might have been eliminated by a longer time of impregnation, it is also pointed out that the elimination of such locally deficient spots is facilitated by the use of thinner insulation. In considering reductions in thickness of insulation, it is suggested that the manufacturers might very profitably give more careful consideration to the actual causes of the failures which have occurred with the present thicknesses.

In paragraph (a) of his discussion, Mr. Shanklin claims a reduction in thickness of oil-filled insulation for 66-kv. cable from 0.40 and 0.42 inch to 0.35 and 0.375 inch. In considering this claim, it should be noted that the thickness of oil-filled insulation on the cable installed a year or two ago by the Central Electricity Board in England was 0.355 inch.

Mr. Shanklin lays great stress on the reduction in the factor of safety which results from a reduction in the thickness of either type of insulation. It is not the percentage reduction in factor of safety that is important, but rather the factor of safety of the reduced insulation. All of our information indicates a high factor of safety with the reduced thicknesses of insulation which have been advocated and with the high quality of insulation now obtainable.

Referring to Mr. Shanklin's comparison of the two types of insulation for various operating voltages, apparently the best reply is to reiterate a paragraph from the paper, as follows:

"Whether the oil-filled type will displace the ordinary type of 66 kv. and lower voltages or the ordinary type compete with the oil-filled type at 132 kv. depends on the relative rates of improvement in the two types of insulation with unrestricted competition."

Mr. Shanklin's concluding paragraph hardly gives the American manufacturers due credit. N.E.L.A. records show that all high-voltage cable made in the past three years averages well below two insulation failures per 100 miles per year.

Mr. Del Mar is in error in stating that my paper shows that 66-kv. single-conductor, oil-filled cables can now compete with cables of the ordinary type between 40,000 and 115,000 kva. He seems to have drawn his conclusions from Fig. 8 of the paper, but this includes only the cost of the cable installed in the conduit, without conduit, joints or accessories. Fig. 12, however, shows that the annual charges for 66-kv. cables of the ordinary type are below those of the oil-filled cable for the entire range mentioned by Mr. Del Mar.

Mr. Del Mar also intimates that my recommendations for reduced thickness of insulation were obtained from "laboratory-made samples and from factory-made lengths of outstanding merit." If the results of the tests on the few laboratory-made samples were entirely neglected, the conclusion would not be altered. I cannot object to Mr. Del Mar's statement that the factory lengths tested were of outstanding merit, but I will add that the lengths tested were sufficient in number to insure that they were typical and representative of entire shipments on commercial orders, and the conclusions from these tests have been confirmed by a perfect operating record of the same shipments, which now amounts to over 400 mile-years, without any insulation failures. As this cable has withstood not only heavy continuous loads, but also variable loads without appreciable deterioration, this record appears to be a sufficient answer to Mr. Burd's comment at the end of the first paragraph of his discussion.

In reply to Dr. Whitehead's question, it does not appear proper to allow an increased credit to the oil-filled type of insulation because of its lack of deterioration, as it appears perfectly possible to secure at the present time the ordinary type of insulation that will not deteriorate in service.

Dr. Whitehead's comments on the gradual rising of power-factor-voltage characteristic of the oil-filled cables with reduced insulation are very interesting. Theoretical considerations indicate that a horizontal characteristic within the operating range would be advantageous, but if a cable that initially has a slightly increasing characteristic will acquire a horizontal characteristic under operating conditions in about one year's time, it is questionable if the added expense of obtaining an initially horizontal characteristic is warranted.

It is interesting to note Dr. Wiseman's prediction that better results can be obtained with the ordinary type of insulation by using a more fluid oil for the impregnating compound. This is in accordance with my suggestions in meetings with the cable manufacturers for many years. It is also interesting to note that he hopes to be able to produce a successful 132-kv. cable with solid type of insulation. This would be quite within the prediction in my paper. With reference to his prediction regarding three-conductor 66-kv. cable, it may be noted that three-conductor 60-kv. "solid" type cable has been in operation in Paris for a few years.

Extinction of Short A-C. Arcs

BY T. E. BROWNE, Jr.*
Associate, A. I. E. E.

Synopsis.—*This paper presents the results of a study made with short, stationary a-c. arcs between metallic electrodes, in order to determine the effect of arc length, electrode material, and current magnitude on the rate of recovery of dielectric strength of the arc space following a current zero.*

The experimental results show (1) that the arc space recovers the ability to withstand a hundred volts or more within a few microseconds after a current zero, as predicted by Slepian's theory, (2) that the maximum allowable rate of rise of voltage across the arc space which will just permit arc extinction is much greater for very short arcs (1 cm. or less) than for longer arcs, (3) that the critical rate of rise of voltage depends largely on the electrode material used and tends to vary as a decreasing linear function of the boiling point, and (4) that the higher current arcs have a much lower critical rate of rise of voltage than the lower current arcs.

* * * * *

I—INTRODUCTION

THE extinction of an a-c. arc, which normally occurs at a current zero, has been shown[1] to depend upon the outcome of "a kind of race" between two opposing processes taking place within a very short period embracing the moment of zero current. The first is the building up of voltage across the arc space tending to cause the arc to reignite, and the second is the diminishing of the conductivity of the arc space, or the increasing of its dielectric strength, tending to prevent the arc from restriking. The first depends on the constants of the circuit and so can theoretically be calculated. In practise, it may be approximately determined if the circuit involved is sufficiently simple. The second process, with which this paper will deal, depends on the characteristics of the arc itself, which are exceedingly complex and as yet understood to only a very limited extent.

II—SHORT ARCS IN ELECTRICAL ENGINEERING

Short arcs are employed in all circuit interrupters, such as knife switches, snap switches, and fuses, operating in a-c. circuits of less than 150 volts. They may also occur as the result of faults in low-voltage circuits and machinery, and in this connection are of very great importance in the case of the modern secondary network used for distribution of low-voltage power in congested city districts. Here the working voltage is limited by the necessity for self-extinction of arcs following "burning clear" of faults, without interrupting the power supply. The extinction characteristics of short a-c. arcs are also made use of in the deion air circuit breaker, where a large number of short arcs is placed in series for operation at higher voltages.[2]

III—REVIEW OF THEORY OF EXTINCTION OF SHORT A-C. ARCS

According to the modern theory of conduction in gases, the rapid recovery of dielectric strength by an arc space immediately following a current zero must be due to the disappearance of the ions which are required for conduction of the arc current. These ions are lost from an arc space in air at atmospheric pressure in three principal ways: first, by recombination of positive and negative ions throughout the space; second, by diffusion from the space to the electrode surfaces and into the surrounding cooler air; and third, by formation of an almost completely deionized layer adjacent to the cathode by the action upon the ions of the growing impressed electric field.

Simplified calculations made by Slepian,[1] assuming ions to be lost from the arc space only by direct ion recombination, predicted a manner of recovery of dielectric strength substantially the same as that actually revealed by experiments made on cold-electrode arcs. These experiments were made by controlling the rate of recovery of voltage across the arc space following a current zero by shunting the arc with resistance. The maximum allowable rate of rise of voltage was determined from the maximum value of shunting resistance at which the arc would just be extinguished after one half cycle. It seemed desirable to repeat these experiments on the more common type of stationary arcs with molten electrodes such as occur in electrical engineering, and to determine the influence upon the arc characteristics of such parameters as electrode material, current strength, and arc length.

IV—EXPERIMENTAL RESULTS

In general, the manner of dielectric recovery following a current zero, of short, stationary a-c. arcs with molten electrodes, was found to conform to the predictions of Slepian's theory and to be similar to the recovery of rapidly moving cold-electrode arcs previously investigated. That is, for electrodes whose boiling temperatures are below that required for appreciable thermionic emission, the ability to withstand a hundred volts or more was recovered within a few microseconds after a current zero, and further dielectric strength was regained at a very much lower rate. This is shown by the curves of Fig. 1 which are noticeably similar to the curve first obtained and published by Slepian[3] of dielectric recovery with time of the cold-electrode arc.

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*Research Laboratories, Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.

[1] *Extinction of an A-C. Arc*, J. Slepian, TRANS. A. I. E. E., 47, 1928, page 1398.

[2] *Theory of the Deion Circuit Breaker*, J. Slepian, TRANS. A. I. E. E., 48, 1929, page 523.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

[3] *Extinction of a Long A-C. Arc*, J. Slepian, JOURNAL A. I. E. E., April 1930, page 310.

As predicted, the initial very rapidly recovered dielectric strength was found to depend solely on the electrode material and gas medium, and not at all on any other conditions within the limits investigated. The further more slowly recovered dielectric strength did not, however, prove to be independent of such conditions as arc length and current magnitude, as Slepian's approximate theory predicts that it should.

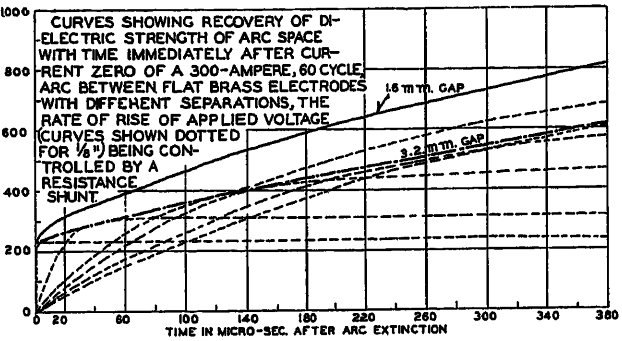

Fig. 1

This simply indicates, as expected, that factors neglected in the simplified theory, such as diffusion of ions to the electrodes and to the surrounding air, the electric field, and temperature variations, are not actually negligible.

IVa—Effect of Arc Length

The effect of length of the arc on recovered dielectric strength was found to depend on the electrode material used. In the first series of tests made with brass electrodes, the effect of arc length was very striking and at first sight seemed paradoxical. As shown in Fig. 1, the dielectric recovery of a 0.158-cm. arc was considerably more rapid than the recovery of an arc of twice that length under otherwise similar conditions, indicating that the shorter arc is easier to extinguish than the longer. This effect is shown in a still more striking manner by plotting the initial slopes of critical applied voltage curves, like those shown dotted in Fig. 1, against arc length, as in Fig. 2. This shows that the effect extends up to five cm. or more, but is most pronounced at lengths of less than one cm. A similar but still more pronounced effect was observed with metals of lower boiling point than that of brass. With electrodes of the higher boiling metals, however, such as copper, iron, and tungsten, the effect was very much less and reversed its direction at the shorter lengths. This is illustrated by Fig. 3, which is the curve of Fig. 2 for brass, redrawn to a different scale and compared with similar curves for mercury, zinc, copper, iron, and tungsten-electrode arcs. The curves for copper and iron are seen to coincide practically with that for brass near five mm. and above and to exhibit the same falling characteristic above about four mm.; but below this length, instead of rising rapidly with diminishing length as with the lower boiling metals, they fall off again; the curve for iron rapidly approaching zero and the curve for copper falling and then apparently tending again to turn upward at the shortest lengths investigated. With the very refractory metal tungsten, the curve is much lower even than with copper and iron, but still appears to reach a maximum at some arc length less than one centimeter and to fall off with increasing length above that.

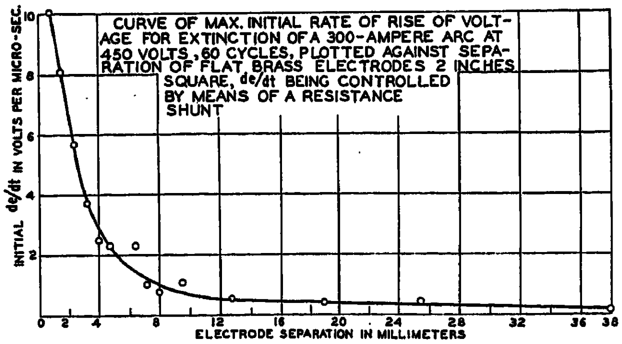

Fig. 2

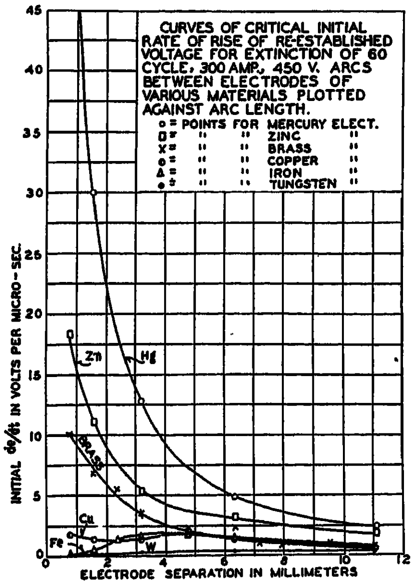

Fig. 3

IVb—Effect of Electrode Material

As already shown, the behavior of a short a-c. arc depends very largely on the material of the electrodes. Fig. 4 shows the results of a series of experiments on 300-ampere, 60-cycle, 450-volt arcs, 0.079-cm., 0.158-cm., and 0.316-cm. long, using various metallic elements as electrodes. The critical initial rate of rise of voltage as measured by the critical shunting resistance for arc extinction is plotted in each case against the boiling point of the element. The interesting and surprising feature of this graph is the definite tendency for the points at each arc length to fall on intersecting straight lines. This approximately linear manner of variation with boiling point applies to all the metals for which results were obtained except mercury, which has values at about twice those required to fit the straight lines, and magnesium, aluminum, manganese, molybdenum, and tungsten (not shown), which either form stable refractory oxides or themselves boil at high enough temperatures for copious thermionic emission, thus preventing the immediate recovery of dielectric strength which characterizes the non-refractory metal arcs.

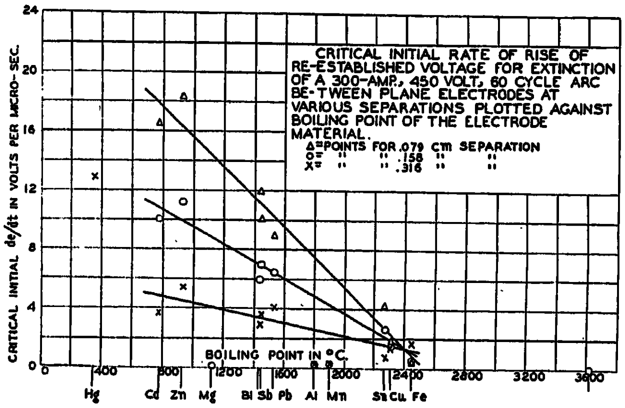

FIG. 4

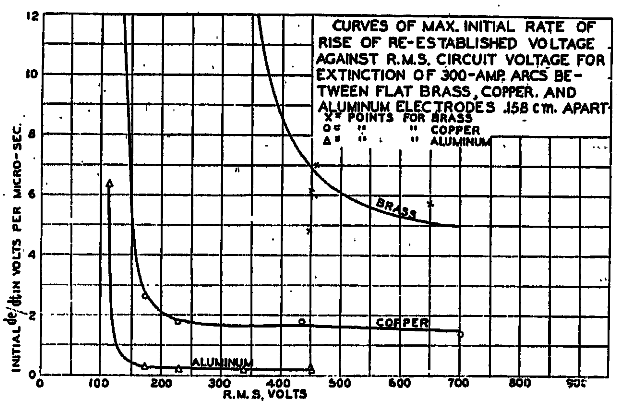

FIG. 5

In Fig. 5, the performance of aluminum, copper, and brass-electrode arcs is shown comparatively in the form of curves of critical initial rate of rise of re-established voltage plotted against the effective circuit voltage at which the values were obtained, other conditions than voltage remaining the same. Remembering that the ordinates of any one of these curves may be considered as a measure of the speed with which the arc space regains the ability to withstand voltages equal to the maxima of sine waves having the effective values given by the abscissas, it may be seen that 0.158-cm. arcs with aluminum electrodes require a very much longer time to recover ability to withstand a given voltage than do arcs of similar length, between copper electrodes, and that 0.158-cm. copper-electrode arcs in turn recover dielectric strength very much more slowly than do 0.158-cm. brass-electrode arcs, other conditions being equal. The rapid rise of all of these curves at the lower voltages is attributed to the approach of the maximum voltage values to the minimum dielectric strength of the cathode space charge sheath, which is recovered in practically zero time. This initially-recovered dielectric strength is approximately 160 volts (maximum) for both copper and aluminum arcs, but is nearly 230 volts for brass-electrode arcs. Because of the scale used, the upper portions of the curves for copper and brass are not shown in this figure.

IVc—Effect of Current Magnitude

The simplified theory, already referred to, predicted that the dielectric recovery of a short arc space should also be independent of magnitude of the arc current, but this prediction depended on the assumption that ionic diffusion to the surrounding air is negligible, which can be true only if the diameter of the arc is large in proportion to its length. Even for arcs only 0.158 cm. long, this condition is approached only at currents of more than a thousand amperes or so; therefore independence of current magnitude may be expected only with currents of this order. Fig. 6 shows this to be the case for a 0.158-cm. copper arc at 450 volts; current variations produce little change in the rate of dielectric recovery above 1,500 amperes, but below this value, decreasing the current causes a rapid increase in speed of dielectric recovery. Below about 150 amperes, the behavior of the arc becomes increasingly erratic so that definitely consistent values of a critical initial de/dt were very difficult or quite impossible to determine. Tests made by F. C. Todd[4] with the cathode-ray oscilloscope show that the restriking voltage of continually restriking arcs is extremely variable when the current is as low as 90 amperes.

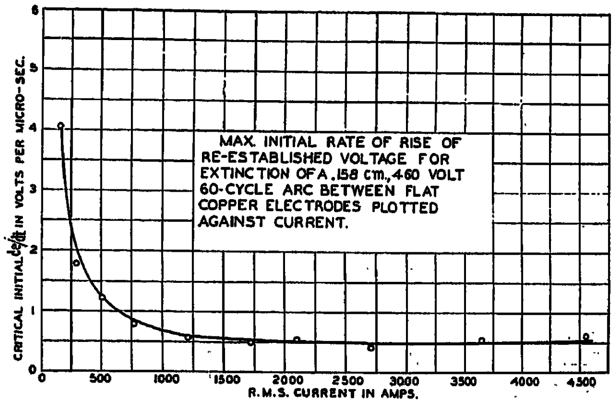

FIG. 6

V—Application to Engineering Practise

In view of the results here presented, some suggestions may be made with regard to the construction of low-voltage circuit-interrupting apparatus or of circuits where extinction of low-voltage a-c. arcs resulting from faults is important. Because of the marked superiority of short brass-electrode over short copper-electrode arcs with regard to speed of recovery of dielectric strength at current zero, it would seem advisable to use brass for the contact breaking parts of low-voltage switches working near their limit. Even where final dependence is placed on drawing out to sufficient length to insure extinction of the arc, use of brass might conceivably result in quicker opening of the circuit with less resulting flame and burning of the contacts than when copper is used. Similarly, aluminum is evidently inferior to copper as a contact breaking material, from the standpoint of extinguishing the arc while it is still short.

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[4] "Restriking of Short A-C. Arcs," F. C. Todd and T. E. Browne, Jr., *Phys. Rev.*, pages 732-737, Vol. 36, Aug. 15, 1930.

Since, as already mentioned, the problem of extinguishing short a-c. arcs is of particular importance in the operation of secondary distribution networks, the above suggestions in regard to use of brass, copper, and aluminum may seem to apply with even more force here than they do to switch construction. Thus the possibility is suggested that the permissible operating voltage of secondary networks might be raised if brass conductors were used instead of copper conductors. Again, use of aluminum as conductor material in place of copper would seem inadvisable from the standpoint of arc extinction. These results, however, must be interpreted with caution when applying them to a problem such as this having such varied practical aspects. In regard to the possible choice between brass and copper as conducting materials where they would also act as electrodes in case of arcing faults between conductors, it should be noted in Fig. 3 that the difference in favor of brass applies only when the length of the arc is less than five millimeters. Consequently, if the arc should be commonly longer than this, brass probably would be no more effective than copper in aiding its extinction. Sufficient data for a similar curve for the aluminum arc have not yet been obtained, but it can be predicted with reasonable certainty that the inferiority of aluminum to copper will be at least greatly reduced at arc lengths of a centimeter or more.

It may be noticed, also, that there is a discrepancy between practical experience with faults in secondary networks and the results given here, in that faults are commonly cleared on networks at as high as 230 volts (r. m. s.) whereas in the laboratory high-current copper-electrode arcs 0.158 cm. long could be easily maintained at as low as 113 volts. This may be due to less severe circuit conditions in the case of the practical network caused by a fairly high power factor on short circuit and the presence of distributed capacitance of the cables and of shunting resistance in the form of connected lighting load, all of which tend to decrease the rate of recovery of voltage across the arc space at a current zero and so allow time for deionization of the arc and recovery of dielectric strength. Probably of more importance, however, is the deionizing action of gases resulting from burning of the cable insulation, the action of which is similar to that of gases from the decomposing oil in an oil circuit breaker.[3]

Before closing, mention must be made of the fact that some of the principles described in this paper have been known in a general way for a long time, and moreover, have been applied to commercially successful devices. The writer refers to the lightning arresters developed by Mr. A. J. Wurts and described by him as long ago as 1892.[5] In this remarkable paper the author states, "The smaller the air gap (with zinc, brass and antimony electrodes) the less the tendency there is to maintain an arc when using an alternating current at 1,000 volts pressure." And also, Mr. Wurts experimentally determined a list of so-called "non-arcing" metals in which zinc, cadmium and zinc-brass top the list. It is to be regretted that modern testing equipment was not available to this genius.

ACKNOWLEDGMENT

Much of the success so far achieved in this investigation must be ascribed to the active cooperation of and inspiration given by Dr. J. Slepian and Mr. F. C. Todd.

Discussion

D. C. Prince: It is rather surprising that Mr. Browne's paper and other previous papers to which it refers should ignore some very prominent arc characteristics which cannot help but be an important factor in circuit interruption. No mention has been made of the rectifying effect of arcs in general and especially metal vapor arcs.

When an arc is drawn between metal electrodes, the mechanism of conducting the current is considered to be substantially as follows:

Electrons proceed from the negative electrode striking, after a short distance, neutral vapor or gas molecules which are ionized. The resultant electrons are added to the electrons initially emitted and progress toward the positive electrode or anode. The positively charged molecules or positive ions formed by the collision are drawn back toward the negative electrode where they form a positive ion space charge film, which results in a high potential gradient at the surface of the negative electrode. The positive ions falling into the negative electrode heat it to the boiling point. If the metal is low melting material such as copper, brass, etc., the boiling point is not accompanied by a sufficient temperature to emit considerable numbers of electrons thermionically. The emission on the contrary takes place by what has been termed cold cathode effect, *i. e.*, electrons are drawn from substantially cold (in the emission sense) metal because of the high potential gradient set up by the positive ion space charge. If the current is momentarily interrupted, the distribution of ionization will, of course, not remain the same. The cathode spot, as the area is known from which the electrons are emitted, immediately ceases to exist and the high potential gradient produced by the positive ions falls off rapidly. Therefore, if the arc is to continue, the impressed voltage in the same direction must be somewhat higher than the voltage across the arc while it was being maintained. These considerations would lead one to expect that the voltage required to reestablish an arc in the same direction would increase more or less continuously with time from the voltage required to maintain the arc.

On the other hand, if the test procedure involves the use of alternating current, the condition after a current zero is that a cathode spot must be formed on the opposite electrode to that on which it was prior to current zero. Immediately after the current zero, the distribution of charges is substantially identical with that immediately before the current zero. There is thus no high potential gradient present at the surface of the new cathode, and therefore an impressed potential different from and greater than the drop in the arc preceding the current zero must be provided if an arc is to start. This arc is really a new arc and not a continuation of the old arc. It flows in the other direction. It has a cathode spot located on an electrode where there was none before and its starting is only facilitated by the fact that there are ions present which can be rearranged so as to produce a high potential gradient close to the surface. This condition, which has received a great deal of study over a number of years, is essentially the same as that which exists in rectifiers.

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[5] "Lightning Arresters," A. J. Wurts, TRANS. A. I. E. E. Vol. 9, 1892, page 102.

In the case of high melting material, such as tungsten, etc., the positive ion bombardment of the cathode tends to bring the latter up to the emission point where it may remain for a considerable time due to heat stored in the metal. The electron bombardment of the anode or positive electrode will heat the latter also up to the emission point so that the rectifying effect is very largely absent.

These considerations should tend to explain the marked difference in behavior of low and high melting materials noted by Mr. Browne. The arc phenomena are naturally made up of two parts, those due to the electrodes of which the cathode is predominant, and those due to the arc stream itself. In short arcs, such as those under consideration, the arc stream deionization effects which have been discussed at such length tend to become secondary. The cathode spot phenomena assume a predominant role in explaining the behavior of short a-c. arcs.

T. E. Browne, Jr.: The reference made by Mr. Prince to the so-called "rectifying effect" of a short metal vapor arc as a factor better able to explain the observed short-arc extinction phenomena than existing theory[1,2] is rather puzzling. It is true undoubtedly that the metal vapor rectifier is essentially a circuit-interrupting arc device and therefore that the same general theory of electric conduction in gases applies to it as to ordinary a-c. arc devices, but, since the rectifier is a more complex and highly specialized piece of apparatus, it would seem to be more natural to use analogies based on the older and simpler devices in describing rectifier phenomena rather than to reverse the process. Also, the rectifier approach of Mr. Prince may be actually misleading, since it would seem to suggest that the reignition of an a-c. arc in the reverse direction after a current zero should be essentially different from reignition in the same direction, and therefore require a different minimum voltage. However, the results of experiments conducted by Attwood, Dow, and Krausnick,[3] using a cathode-ray oscillograph, indicate that no such condition exists in the case of short arcs between similar electrodes symmetrically placed.

The importance of thermionic emission from refractory electrode materials, mentioned by Mr. Prince, has been pointed out in a previous paper,[2] but the large effect of electrode boiling point in the case of the low-boiling metals, as illustrated by Figs. 3, 4, and 5 of the paper, probably cannot be explained on this basis. Although the phenomena that determine the extinction or reignition of a short a-c. arc at current zero do occur, as is generally recognized, at or immediately adjacent to the electrode surfaces, they still take place *in* the gaseous arc space and so must, in general, depend very largely upon the magnitude and rate of change of ionization density in this region. When thermionic emission is lacking, then, the principal influence of the electrode material upon short-arc reignition must be through the medium of its vapor, of which the gas adjacent to the electrodes is mainly composed. The Langmuir high-field theory (or "cold cathode effect") obviously cannot be applied to the process of arc reignition after an appreciable current zero period, since it depends essentially upon the existence of a high current density at the cathode, inasmuch as high current density is essential to the maintenance of the required space charge.

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[1] *Extinction of an A-C. Arc,* J. Slepian, Trans. A.I.E.E., V. 47, p. 1398 (1928).

[2] "Restriking of Short A-C. Arcs," F. C. Todd and T. E. Browne, Jr., *Phys. Rev.*, V. 36, pp. 732-7, (1930).

[3] *Reignition of Metallic A-C. Arcs in Air,* S. S. Attwood, W. O. Dow, and W. Krausnick, Trans. A.I.E.E., Vol. 50, September 1931, p. 854. (Figs. 15 and 16.)

A Corona Tube Voltage Regulator

BY H. W. DODGE* and C. H. WILLIS†
Non-member Member, A. I. E. E.

Synopsis.—A circuit is described whereby a corona tube may be used to regulate the output of a full-wave rectifier and therefore to control the excitation of a generator to give constant voltage. Performance curves are given for a five-kva. generator whose voltage is controlled by such a regulator.

* * * * *

A VOLTAGE regulator consists essentially of a constant element; an element which varies with the voltage and which is balanced against the constant element; and an arrangement for using this balance to control the excitation of the machine whose voltage is to be regulated.

In the familiar vibrating contact regulator the modulus of elasticity of a spring is the constant element. Acting against the spring is the pull of a solenoid which is dependent upon the voltage. The forces due to the solenoid and the spring act on a plunger which operates a contact by which resistance is put into or taken out of the generator field circuit, thereby regulating the generator voltage.[1]

The most serious disadvantages of the vibrating contact regulator are:

1. Wear and sticking of the contacts.
2. Periodic fluctuations of the voltage with opening and closing of the contacts.
3. Slow response of the regulator to fluctuations of the voltage, due chiefly to the time lag of the field circuits of the exciter and the generator.

Recently a number of new types of regulators has been devised. Almost any phenomenon which varies with voltage may be made the basis of a voltage regulator, such as the saturation of an iron core reactor, the resistance of a conductor heated by the voltage, or the internal resistance of a thermionic tube whose filament is heated by the voltage.[2,3] The regulator described below employs the critical voltage of a corona tube as the basic phenomenon.

The corona discharge tube employed consists of two symmetrical electrodes sealed into a glass tube containing an inert gas at a suitable pressure. Due to the fact that the tube contains a definite quantity of gas constrained to a fixed volume, the mean free path of an ion and therefore the corona voltage are practically independent of the temperature. Since ionization builds up very quickly at a voltage above the critical value, the breakdown voltage is also independent of the frequency for frequencies within the commercial range. With the electrodes surrounded by an inert gas such as argon there is negligible disintegration of the electrodes during discharge; the breakdown voltage of the tube is constant and the life very long.

These characteristics of the corona discharge tube make its critical voltage suitable for the constant element in a regulator. The fact that it regulates to a constant peak voltage rather than a constant effective voltage is not a serious disadvantage, for the variation of wave form with load is not appreciable and there will therefore be a constant form factor.

In order to control the excitation of a generator we may use the charge passing through the corona tube above the corona voltage to bias the grid of a rectifying tube and thereby regulate the amount of rectified current which will be supplied to the generator field.[4] Any type of rectifying tube may be used. However the high efficiency and large amplification factor of a gaseous tube, such as the thyratron, make this type of tube very desirable.

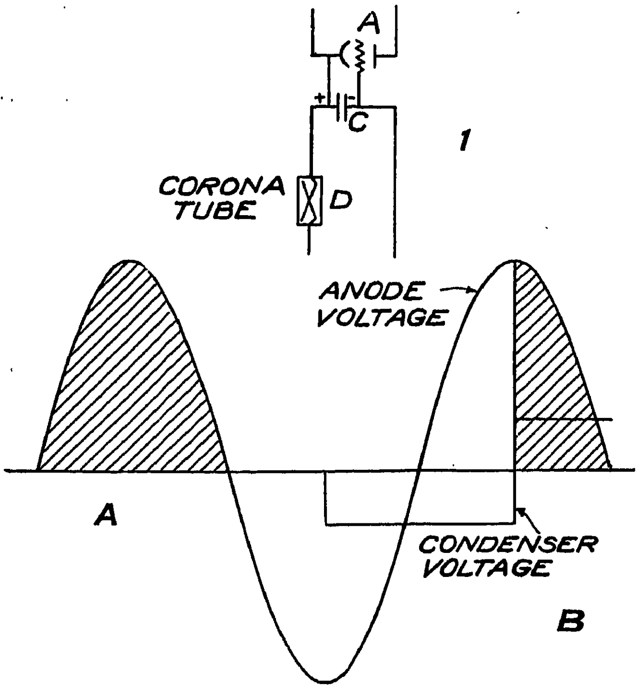

Fig. 1—(Upper) Elementary Grid Bias Circuit
Fig. 2—(Lower) Relation of Anode Voltage to Grid Voltage

Referring to Fig. 1, *A* is a thyratron with a negative grid characteristic, and it therefore normally conducts current into the field of the generator during the half wave when the anode voltage is positive as shown in Fig. 2A.

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*N. J. Bell Telephone Company.

†Associate Prof. Elec. Engg., Princeton University. Temporarily with G. E. Research Lab., Schenectady, N. Y.

1. For references see Bibliography.

Presented at the Summer Convention of the A. I. E. E., Asheville, N. C., June 22-26, 1931.

During the half wave when the anode voltage is negative the condenser *C* will be charged as shown in Fig. 1, provided the circuit is connected with the proper polarity and provided the voltage rises above the critical value for the corona tube. During the first part of the next positive half wave the thyratron cannot conduct current because the grid is negative (see Fig. 2B). However the grid bias will be reversed by the corona tube at the peak of the voltage wave, and the thyratron will conduct current during the latter half of the positive voltage wave as shown by the cross-hatched area. In this way the average value of the rectified current will be reduced to one-half the full half wave or maximum value when the voltage is above the breakdown value for the corona tube.

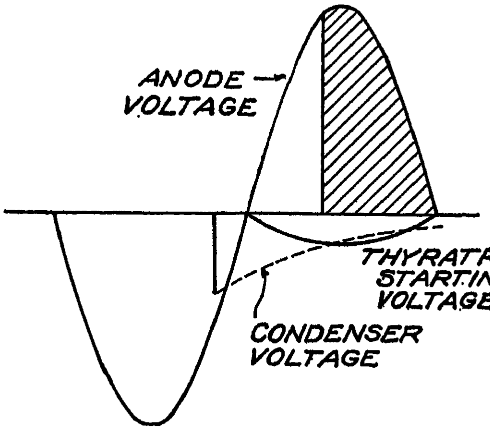

Fig. 3—Relation of Anode Voltage to Grid Voltage Using a Grid Leak

If a voltage is impressed on the corona tube which lags in phase behind the rectifier voltage, the average current may be reduced to less than 50 per cent of its maximum value because the grid bias will then be reversed after the peak of the voltage wave. When the corona tube is supplied from a voltage 60 degrees behind the rectifier voltage as in a three-phase machine, the corona tube will reduce the average current to 7 per cent of the maximum value.

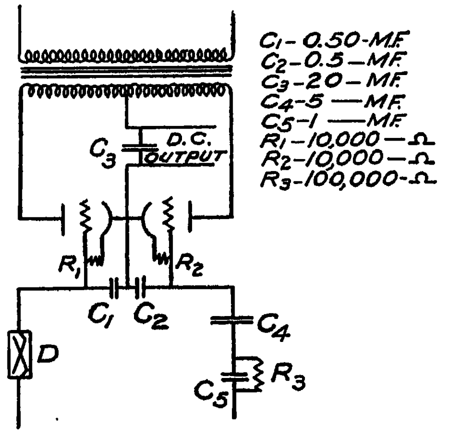

Fig. 4—Corona Tube Voltage Regulator Circuit

The circuit as described above will vary the excitation by definite steps and will give fluctuations in the excitation just as are produced by opening and closing the contacts of a vibrating regulator. However if a leak is placed across the grid biasing condenser of a value such that the time constant *C R* of this condenser and leak is about equal to the period of one-half wave, then the grid condenser voltage may be reduced by leakage to a value where the thyratron will start. The time it will take to reduce the grid voltage to the starting value will depend on the initial charge of the grid condenser, and this is determined by the excess of the voltage above the critical voltage of the corona tube. Therefore the time of starting for the thyratron rectifier in any half wave will be delayed by an amount which is determined by the excess of the voltage above the breakdown voltage of the corona tube (see Fig. 3). A small rise in total voltage above the critical value will serve to reduce the rectified current to about 7 per cent of its maximum value. However this change is continuous.

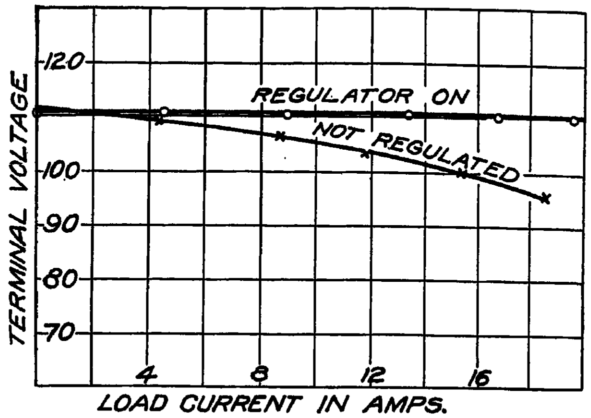

Fig. 5—Operation Regulator with Variable Load

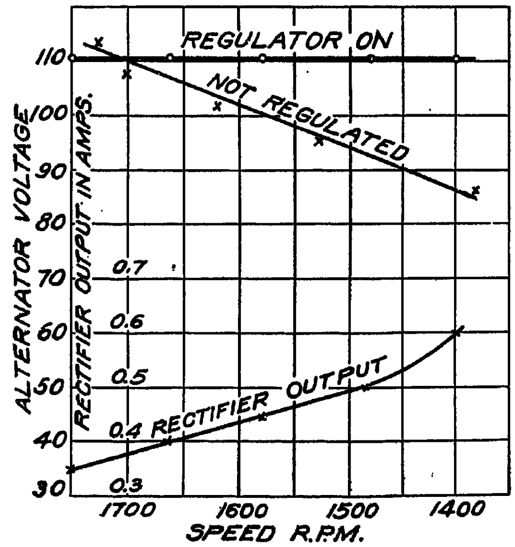

Fig. 6—Operation of the Regulator with Variable Frequency

Fig. 4 shows the circuit used for controlling a full wave rectifier by means of a corona tube. It was found quite difficult to make corona tubes so symmetrical that they would break down at the same voltage on the positive and negative half waves. However by adding the condenser C_4 shown in Fig. 4 it is possible to eliminate any unidirectional components of current and cause the corona tube to have the same positive and negative critical values.

In the regulator used for the results given below, the thyratrons were too small to rectify the entire field current and their output was used for the field of an exciter.

In this case a further difficulty arose in the time lag of the exciter and alternator fields in responding to a change in the rectifier output. This caused oscillations of the generator voltage of about the period of the time constant of the field circuit. It was found possible to suppress these oscillations by introducing into the corona tube circuit a transient of about the same period as the oscillations. This transient is introduced by a condenser with a leak as shown at C_5 and R_3 of Fig. 4, such that $C_5 R_3$, the time constant, is about equal to L/R, the time constant of the slowest field circuit.

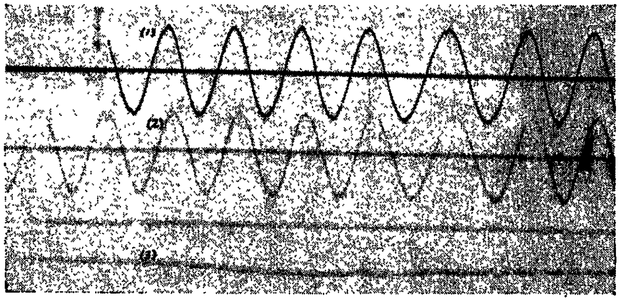

FIG. 7—(1) LOAD CURRENT
(2) ALTERNATOR VOLTAGE
(3) REGULATOR OUTPUT

The constants of the regulator circuit as used are shown in Fig. 4. The critical voltage of a corona tube with given dimensions and gas pressure may be predicted from the data giving the corona voltage of the gas to be used.[5] The tube as used contained argon at a pressure of two centimeters of mercury. The electrodes were parallel wires 0.25 mm. in diameter and separated 1 cm. The critical voltage of this tube was approximately 350 volts peak value.

The results shown in the curves of Figs. 5 and 6 were taken on a 5-kva. three-phase motor-driven alternator excited from a 110-volt motor-driven exciter. In the curves of Fig. 5 are shown the effects of load variation while Fig. 6 shows the regulation when the speed of the driving motor is varied. The oscillograms shown in Fig. 7 shows the transient conditions when full load was suddenly thrown on the generator.

This type of regulator would employ the same methods of compounding and line drop compensation now in use. It is believed that the simplicity, compactness, high sensitivity, and quick response of this regulator offer advantages over the other types.

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Discussion

W. B. Kouwenhoven: The authors of this paper have presented in condensed fashion a description of a voltage regulator that is apparently quite simple and at the same time possesses no moving parts. In our work on dielectrics at Johns Hopkins University the accurate control of frequency is essential. I should like to ask the authors if it is possible to apply their system to the control of frequency. I should also like to have them give a complete diagram of the circuits involved, assuming that the source of supply is a 115-volt a-c. generator driven by a 230-volt d-c. motor. It would be of interest to know how closely the frequency may be controlled.

C. H. Willis: Several methods have been developed for controlling motor speeds by the use of thyratrons. We have used a tuned bridge to control the grids of the tubes which supply the field current of a shunt motor. This method is capable of giving very accurate speed control, but the time constant of the field circuit makes it very slow in responding. Work is now in progress on this subject and I hope to be able to present further information on this subject later.

Experimental Studies of Arcing Faults on a 75-Kv. Transmission System

BY J. R. EATON,* J. K. PECK,† and J. M. DUNHAM‡
Associate, A. I. E. E. Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—*Qualitative results of an investigation, in which high-voltage impulses were applied to an energized transmission line, indicate that the probability of a lightning flashover developing into a power arc is increased when current is flowing past the flashover point, and when the normal frequency voltage is increased or the insulation decreased.*

An oscillographic study of power arcs ranging in magnitude from 8 to 800 amperes indicated that the resistance of an arc varies over the cycle and over the duration of the arc. The effective arc resistance is approximated by the ratio of the peak voltage to the peak current. The apparent power factor of the arc current and voltage is practically unity in most cases. The tests indicated that arcs formed in a capacitive circuit are more persistent than those in inductive or resistive circuits, and that the average peak volts per foot of arc length, for currents above 100 amperes peak, is about 300.

The maximum overvoltage recorded on an isolated neutral 75-kv. transmission system, 134 miles in length, as a result of 63 arcing ground tests was 3.0 times normal on a sound phase. The overvoltage is essentially a fundamental frequency phenomenon in which the sound phase voltage takes its new value without going through an oscillation of appreciable magnitude.

* * * * *

INTRODUCTION

A DISCUSSION of the continuity of service which can be maintained on a power system frequently involves the consideration of power arcs. In cases where power and communication systems occupy the same territory, the consideration of power arcs to ground is also important from the standpoint of their reaction on communication systems. In spite of the importance of arcs in the operation of power systems, there is but little available experimental information on the causes of power arc follow-ups due to surges, characteristics of arcs, or the resulting effects of arcs.

This paper presents the results of cooperative experimental investigations made by the Consumers Power Company, the General Electric Company and the Joint D. and R. Subcommittee of the N. E. L. A. and Bell System, to study the character of arcing faults. For convenience in conducting the tests and in preparing the paper, the investigation has been divided into three parts, namely:

1. Factors governing the development of a power arc following impulse flashover.
2. Characteristics of power arcs.
3. Overvoltages due to arcing grounds.

I. FACTORS GOVERNING THE DEVELOPMENT OF A POWER ARC FOLLOWING IMPULSE FLASHOVER

Power arcs resulting from high-voltage transients in electrical systems are characterized by two distinct though closely related phenomena. First, voltage stresses produce a conducting path through the insulating material (ionization by collision) which permits the flow of current commonly known as spark discharge. If in addition to the transient, there is a continuous supply of energy available, certain changes take place resulting in heating of the electrodes (thermal ionization of the dielectric) and a continued flow of current known as an arc. Although the spark and the arc are quite different in nature, there is no sharp line of demarcation between the two, and the transition from one to the other is but little understood.

Operating data presented in the past few years have indicated that frequently lightning may cause sparkover of transmission line insulators without producing a power arc. This fact does not seem particularly surprising when consideration is given to the extremely short duration of lightning transients and to the nature of the a-c. systems on which they are impressed. With the equipment available at Croton an attempt was made to study experimentally the factors governing the transition of an impulse flashover into a power arc. For these tests a setup was made as shown in Fig. 1. By means of a 1,500-kv. impulse generator[1] high-voltage surges were applied to a transmission line conductor which was in turn energized from the transformer bank. Line insulation was so correlated that flashover took place at a predetermined test tower at which spacing *D* was varied at will. During part of the tests, connections were made equivalent to closing switch *A*, thereby

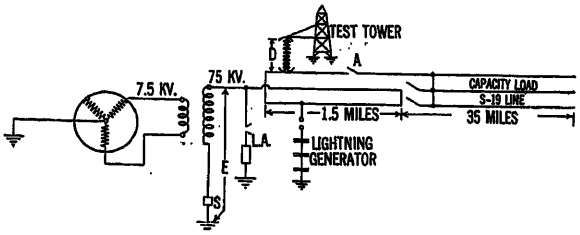

FIG. 1—DIAGRAM OF CONNECTIONS USED IN IMPULSE FLASHOVER TESTS

D—Variable distance between conductor and tower
With line off, switch *A* was open
With line on, switch *A* was closed

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*Consumers Power Co., Jackson, Michigan.

†National Electric Light Association, New York City.

‡American Telephone and Telegraph Co., New York City.

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[1] For references see Bibliography.

causing a normal flow of power current past the test insulator due to the capacity load of 35 miles of the three-conductor transmission line. As no attempt was made to synchronize the impulse generator discharge with the 30-cycle excitation of the line, the point on the 30-cycle voltage and current waves at which flashover occurred was governed entirely by chance. During certain tests, this point was determined by oscillographic measurements of voltage at E and by current measurements at S.

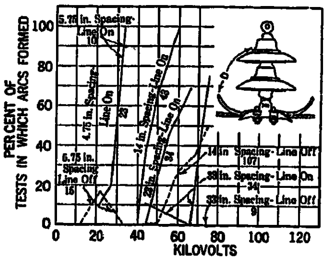


FIG. 2.—PER CENT OF IMPULSE FLASHOVERS WHICH DEVELOPED INTO POWER ARCS AT VARIOUS LINE VOLTAGES AND ELECTRODE SPACING, D WITH AND WITHOUT CAPACITY OF S-19 LINE AS LOAD

Numbers under spacing designation indicate number of tests in group

A total of 278 tests was made under a variety of test conditions. The curves of Fig. 2 show the per cent of sparkovers which resulted in power arcs (as determined by visual observation) for various electrode spacings and various applied values of 30-cycle voltage. These curves indicate several more or less definite tendencies:

1. For given excitation voltage and electrode spacing the flow of capacity charging current past the test insulator increases the probability of a power arc resulting from impulse flashover. This seems quite reasonable inasmuch as arc current is immediately available by the shift of current flow from the line to the arc, without the necessity of overcoming the inductance of the circuit, as would be the case if no initial current were flowing.

2. For a given electrode spacing, the possibility of power arc follow-up is dependent on the value of the normal frequency excitation voltage. Below certain values of voltage, a given insulator assembly apparently is almost immune from power arc follow-up. This critical value of power frequency voltage appears to be considerably higher in test than would be borne out by practical experience on operating lines.

During 66 of the 278 tests conducted, oscillograms of voltage and current were obtained as described above. From these records it is possible to determine the point on the 30-cycle voltage wave at which flashover occurred. Fig. 3 shows diagrammatically the results of these tests plotted according to line voltage and point on the wave at which the flashover occurred, but without regard to electrode spacing or whether current was flowing past the test insulator. This diagram shows that a high percentage of the flashovers occurring near the 90 deg. point of the voltage wave, resulted in power arcs. From a further analysis which is not shown on this diagram, it was found that this grouping of tests near the 90 deg. point was very definite for tests in which current was flowing past the sparkover point, but for the case when there was no current in the line (switch A open) the points were fairly well scattered.

In many of these tests, oscillograms indicated that the sparkover caused a considerable transient in the 30-cycle voltage wave, and in some cases even caused this voltage to fall to zero for a period of 5 or 10 elec. deg., without developing into a power arc. It appears that the development of a power arc is dependent on conditions existing within the first few thousandths of a second after sparkover. It is possible that on systems having large connected generating capacity carrying heavy loads, in which case large arc currents are immediately available, the per cent of sparkovers developing into power arcs may be much higher than is indicated by these tests. It is felt that the conclusions drawn from these experiments must be interpreted as being qualitative rather than quantitative.

II. CHARACTERISTICS OF POWER ARCS

In connection with relaying and short-circuit computations, it is desirable to know, under certain fault conditions, the characteristics of power arcs. The difficulties of investigating experimentally under practical conditions the effect of each of the many variables determining a long arc in air, are manifold. Experimental investigations[2] of arc characteristics have been made from time to time under practical conditions which add considerably to the present knowledge of the behavior of arcs on transmission systems. The tests which are described here deal chiefly with a discussion of the variations in arc resistance, wave shape, persistence of the arc, and arc length, obtained experimentally from 30 tests made under various conditions.

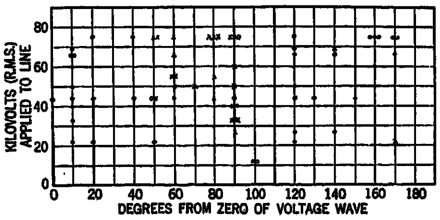


FIG. 3—POINT ON 30-CYCLE WAVE AT WHICH IMPULSE FLASHOVER OCCURRED

X Arc formed
O Arc did not form

Test Setup. The connections for setting up the arc circuit are shown on Fig. 4. In general, the arc was formed in three types of circuits energized at 75,000 or 7,500 volts by pulling a 2-ampere fuse wire between copper electrodes. The major component of the impedance of each of these three circuits was, respectively, resistance, capacitance, and inductance. It should be noted that the phase angle of the impedance of the inductive circuit shown in Fig. 4c was +30 deg. while that of the inductive circuits shown in Figs. 4d and e was nearly +90 deg. The initial arc current for these three types of circuits ranged from 8 to 60 amperes (peak). Arc currents ranging from 200 to 800 amperes (peak) were obtained in an inductive circuit energized at 7,500 volts (r. m. s.). This circuit is shown in Fig. 4e.

Measuring Equipment. The measurements of arc voltage and current were made with a magnetic oscillograph. Shunts were used for current measurements and resistance potentiometers for voltage measurements. Each of these potentiometers consisted of a 25-ft. length of doubled garden hose through which water was circulated by a pump. A metal coupling at one end of this hose was connected to the line, and the voltage drop taken from a short length adjacent to the grounded end. The resistance of this potentiometer was approximately 500,000 ohms. The difficulty of measuring the arc voltage, which varied from the normal line voltage to a very small value, was overcome by the use of two oscillograph elements of different sensitivities. To prevent damaging the high sensitivity element, a spark gap was shunted across a section of the hose which included the section for the high sensitivity element. Breakdown of this gap was recorded by an element connected in series with it. Two moving picture cameras placed at right angles to each other were set up to photograph the arc.

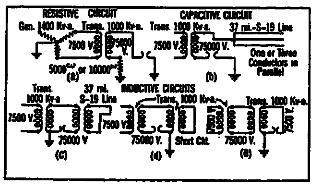
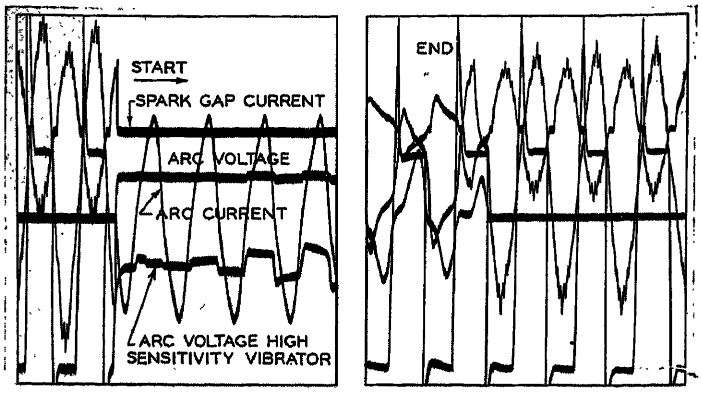


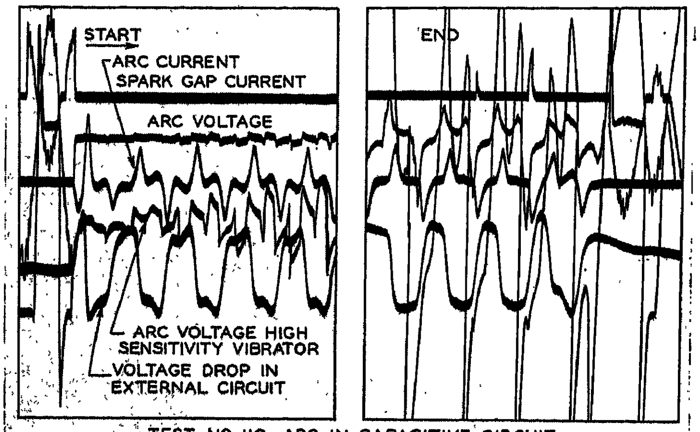
Fig. 4—Connections for Tests on Arc Characteristics

Arc Resistance. Since the resistance of an arc is not constant but is dependent on current, length, wind, etc., some discussion of the variations of resistance, based on experimental data, will be of value. It is proposed here to discuss the experimental data from the standpoint of the variation of resistance over the cycle and throughout the duration of the fault. Typical oscillograms for the three types of circuits employed, that is, resistive, inductive, and capacitive, are shown in Fig. 5 for tests 101, 112, 117, and 123.

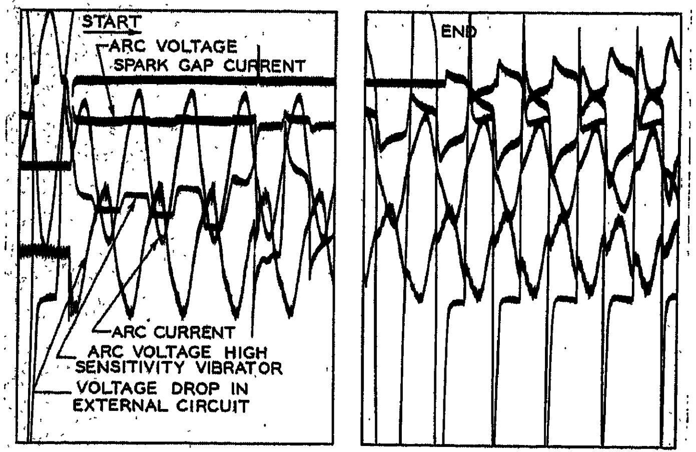
Considering first the variation of instantaneous resistance of the arc over a cycle, that is, the instantaneous voltage divided by the instantaneous current, an analysis was made for a cycle near the start of the arc and one just previous to arc extinction. The curve of resistance of an arc in a resistive circuit (test 101), for a



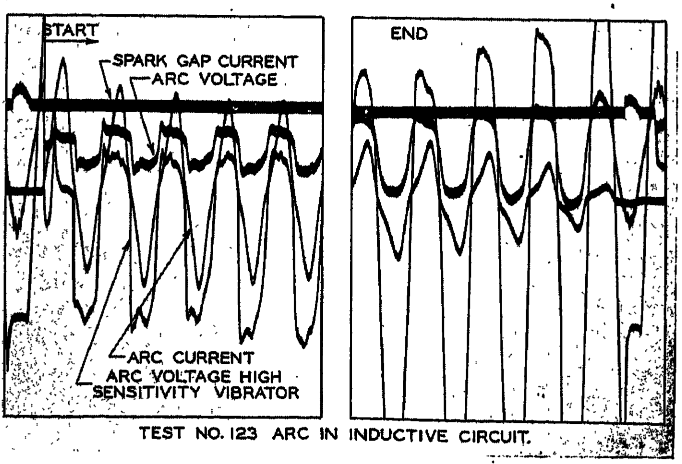
TEST NO. 101 ARC IN RESISTIVE CIRCUIT.



TEST NO. 112 ARC IN CAPACITIVE CIRCUIT.



TEST NO. 117 ARC IN INDUCTIVE CIRCUIT.



TEST NO. 123 ARC IN INDUCTIVE CIRCUIT.

Fig. 5—Typical Oscillograms for Arc Characteristic Tests

cycle near the start and one near the point of extinction, is shown plotted against time in Fig. 6. These curves are of the same nature as the corresponding curves for the inductive and capacitive circuits. Curves corresponding to those for Fig. 6 have been drawn for a higher current arc in an inductive circuit and are shown in Fig. 7. It will be noted from these curves in Figs. 6 and 7 that the instantaneous resistance varies over a wide range between the current zeros, being very large near current zero and reaching a small minimum value at the peak of the current. The increase in instantaneous resistance noted near the point of extinction is due to the lengthening of the arc and the decrease in arc current, and will be discussed later.

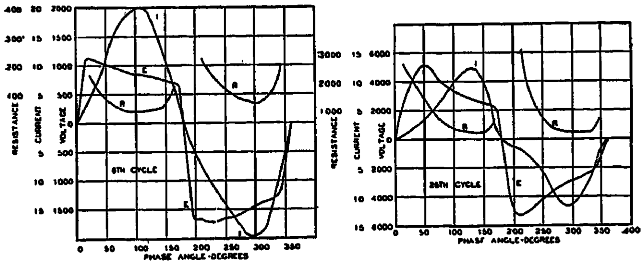


Fig. 6—Curves Showing Relations Between Arc Voltage, Current, and Resistance for a Cycle Near Start of Arc and One Near Point of Extinction

Arc in resistive circuit

The variation of instantaneous arc resistance from cycle to cycle was investigated for all tests. Several points were chosen on the current and voltage waves and measurements of instantaneous resistance were made at these points on succeeding cycles throughout the duration of the fault. The instantaneous resistance corresponding to the peak of the current, peak of the voltage, tail of the voltage (usually a second peak of smaller magnitude than the first), and the ratio of peak voltage to peak current for arcs in resistive and inductive circuits are shown as a function of the duration of the arc in Figs. 8 and 9. During the early stages of the arc, increases in length of the arc path result in increases in arc resistance. This arc resistance, however, is small compared with the external impedance so that there is but little change in current. As the arc resistance becomes a larger per cent of the total circuit impedance due to the increase in length, the arc current is decreased. The decrease in current results in a still further increase in arc resistance. The curves in Figs. 8 and 9 bear out this discussion by showing that the arc resistance in the early stages of the arc is principally dependent on the arc length and is roughly proportional to it, while near the point of extinction the increase in resistance is more rapid, due to the decrease in current.

It follows from the above discussion that the measured value of arc resistance is dependent on its method of determination. If the arc resistance is to be determined from measurements of dynamometer type instruments, which measure r. m. s. values, the effective resistance of the arc will be obtained and it is defined as the ratio of the r. m. s. voltage to the r. m. s. current. The assumption that the arc impedance is practically all resistive is borne out by a subsequent discussion.

A very close approximation of the effective arc resistance was found to be the ratio of the peak voltage to the peak current. This provides a simple method for obtaining the effective resistance of the arc when the current or voltage waves are not sine waves. It should be noted in connection with this approximation for effective resistance that it was found to be true within a few per cent for arc resistances above 10 ohms and the error varied from 15 to 25 per cent for lower values of arc resistance.

Wave Shape of Arc Current and Voltage. In the past there has been some question as to the phase relation between the current in an arc and the voltage across the arc. The oscillograms of current and voltage of an arc shown in Fig. 5 indicate that in these tests the current and voltage waves have simultaneous zeros. However, if the variations in current and voltage are not sinusoidal, the apparent power factor may not be unity. The apparent power factor of the arc was determined by analyzing typical cycles to obtain the ratio of the average of the instantaneous products of current and voltage to the product of effective current times voltage. These analyses indicate a variation in apparent power factor from unity to 0.75 in each type of circuit for current varying up to 60 amperes peak. The high value of apparent power factor occurs near the start of the arc and decreases to the lower value near the point of extinction. In the so-called high-current tests in which the current varied from 200 to 800 amperes the power factor was very nearly unity throughout the duration of the arc. The apparent power factor of the arc current and the voltage at the source, was found to be practically unity for all tests.

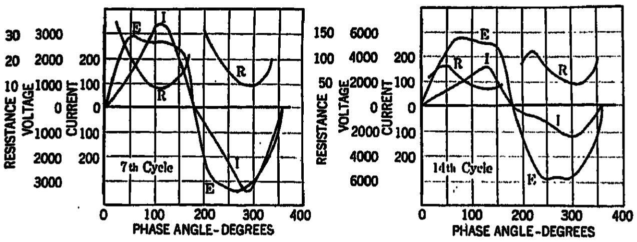


Fig. 7—Curves Showing Relations Between Arc Voltage, Current, and Resistance for a Cycle Near Start of Arc and One Near Point of Extinction

Arc in inductive circuit

In discussing the wave shape of arc voltage and current qualitatively, use will be made of the relationship referred to above, namely that the arc resistance varies inversely with the current, and directly with arc lengths The wave shape of the arc voltage and current is dependent on the type of circuit in which the arc is formed, the characteristics of the arc itself, and the presence of harmonics in the supply voltage. The effects on wave shape of the factors mentioned above are shown on the oscillograms in Fig. 5.

Consider the oscillogram for test 101 in which the circuit impedance exclusive of the arc was principally resistance. For this case the arc resistance at the start of the arc was small compared with the external resistance so that the current is not affected appreciably by the arc and is practically a sine wave. The arc voltage, however, is not a sine wave. This is to be expected since the arc resistance varies over the cycle, being high for small values of current and low for large currents. As the duration of the arc increases, its length increases, resulting in an increase in resistance. As the arc resistance, still varying over the cycle, becomes a larger per cent of the circuit impedance, the current wave becomes distorted and the arc voltage approaches a sine wave.

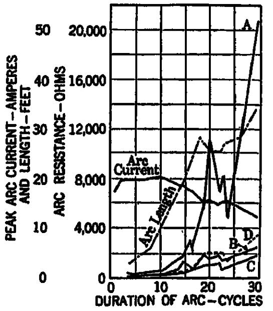


Fig. 8—Curves of Resistance, Current, and Length for Test 101

A Instantaneous resistance for peak voltage
B Instantaneous resistance for tail voltage
C Instantaneous resistance for peak current
D Ratio of peak voltage to peak current

The tests which were made with an arc formed in a capacitive circuit indicated the presence of a very large third harmonic current, as shown on oscillogram 112, in Fig. 5. The reason for this large triple harmonic current is apparent from the nature of the circuit. Any harmonics which appear in the voltage across the arc circuit result in large harmonic currents, since the capacitive circuit affords a lower impedance path for the harmonic currents than for the fundamental current.

Effect of External Circuit on Persistence of an Arc. In forming arcs in three different types of circuits, it was hoped that some information would be obtained on the relation between the persistence of the arc and the type of circuit in which the arc was formed. In spite of the fact that it was impossible to duplicate exactly conditions of wind, current, and wave shape for the different types of circuits, certain conclusions as to the persistence of an arc can be drawn from the experimental data.

The factors determining whether an a-c. arc will be extinguished at current zero have been described by Dr. J. Slepian[3] as, first, the rate of recovery of the voltage across the arc and, second, the ability of the arcing medium to recover dielectric strength. If the rate of recovery of the voltage across the arc exceeds the rate at which the arcing medium recovers dielectric strength, the arc will persist. In this discussion it will be assumed that the recovery of dielectric strength of the arcing medium is the same for each type of circuit.

A comparison, based on whether or not the arc restruck following extinction at current zero, was made of the oscillograms for arcs formed in resistive, capacitive, and inductive circuits. Restrikings of the arc were observed only in the case of the capacitive circuit. This seems to indicate, that if arcs were formed under identical conditions in resistive, capacitive, and inductive circuits, only the arc in the capacitive circuit would persist, following the first extinction at current zero. The arcs formed in the resistive and inductive circuits showed about the same tendency toward extinction, that is, an increase in arc resistance followed by a decrease in arc current to the point of extinction. The oscillograms show that after the arc is extinguished the voltage across the electrodes rises to normal in the resistive and inductive circuits, but rises to approximately twice normal in the capacitive circuit. The rise of this voltage to approximately twice normal in one-half cycle may be explained by the fact that after arc extinction the voltage across the electrodes tends to rise to a value equal to the sum of the generated voltage and the voltage trapped on the equivalent condenser in the circuit.

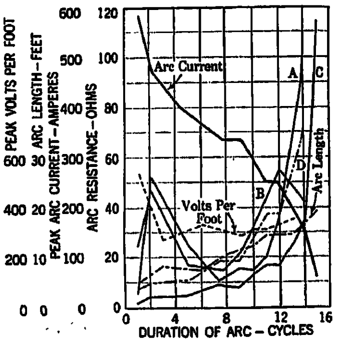


Fig. 9—Curves of Resistance, Current, Length, and Volts Per Ft. for Test 123

A Instanteous resistance for peak voltage
B Instantaneous resistance for tail voltage
C Instantaneous resistance for peak current
D Ratio of peak voltage to peak current

The greater persistence of the arc in the capacitive circuit seems to indicate that not only is the rate of the recovery of arc voltage important but also the maximum value to which this voltage rises.

Arc Length and Arc Voltage. Arc length, arc current, and arc voltage are inter-dependent and are very much influenced by the direction and velocity of the wind and by electrode spacing. Arc length has been determined from measurements of moving pictures taken with two cameras at right angles. The variations of arc length have been plotted against the duration of the arc as shown in Figs. 8 and 9.

Other experimental investigations[2] have shown that a fairly definite relation exists between the voltage across an arc and the length of the arc. This relation may be expressed in peak volts per foot of length. To observe the effect of variation of arc current on the peak voltage per foot of arc length, a "shot gun" diagram was made and is shown in Fig. 10. The points plotted on this diagram represent the peak voltage per foot, computed for various tests and for several cycles of each test. This diagram indicates a very definite grouping at 300 volts per foot for currents greater than 100 amperes peak. For currents below this value, there appears to be no definite grouping.

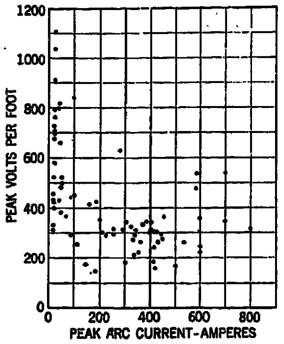


Fig. 10—Plot Showing Arc Voltage Per Foot of Arc Length for Various Currents

Conclusions. 1. The resistance of an arc varies over the cycle and over the duration of the arc, so that it becomes necessary to define arc resistance with regard to the particular use for which it is intended. The effective resistance is important in the operation of certain types of relays and this is approximated fairly accurately by the ratio of the peak voltage to the peak current of the arc.

2. The arc current and arc voltage have simultaneous zeros. The apparent power factor of the arc current and voltage was found to be as low as 0.75 under certain conditions, but in general it can be considered as unity. Due to the nature of the arc, either the arc current, the arc voltage or both may be distorted.

3. The arcs formed in the capacitive circuit showed less tendency to extinguish than those in the inductive or resistive circuits. Arcs formed in either the resistive or inductive circuit showed about the same tendency to be self-extinguishing.

4. The average peak volts per foot, for arcs ranging in current from 100 to 800 amperes peak was found to be 300 volts per foot.

III. Overvoltages Due to Arcing Grounds

Opinions vary rather widely, regarding the maximum overvoltages which can be developed on an isolated-neutral transmission system at the time of an arcing ground, according to whether they are based on theoretical considerations, laboratory tests or limited operating data. From the tests on an actual transmission system herein described, information on the nature and magnitude of such overvoltages was sought. The term "arcing ground" as used in this paper refers simply to the condition of a transmission line fault to ground through an arc, and the term "sound phase" refers to either one of the two unfaulted phases. Overvoltages are expressed in terms of the ratio of the maximum peak voltage to ground during a fault, to the same peak voltage just previous to the fault, the latter quantity being referred to as normal voltage.

Nature of Tests. A three-phase transmission line, open at the far end, was energized at 75 kv. by a generator and transformer bank as shown in Fig. 11. The characteristics of the S-19 and T-20 transmission lines, which were used in the tests, are given in Fig. 11. Arcing ground faults were produced on phase M conductor at different points on the line. These faults were initiated in the following manner:

1. A grounded copper wire or a fuse wire was pulled into the line.
2. A grounded conductor was pulled into and away from the line, or held within arcing distance of the line.
3. A grounded green oak stick was swung close to the line.
4. A line conductor was swung above the sandy soil.

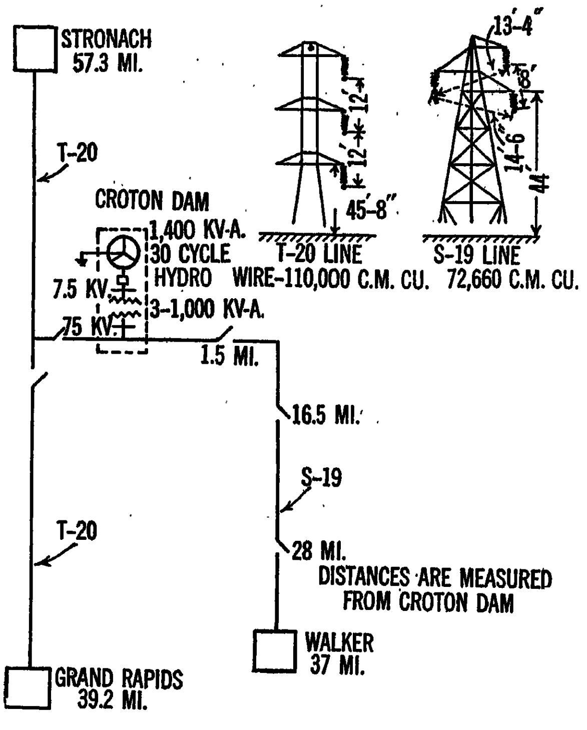


Fig. 11—Layout and Configuration of Transmission Line

Oscillographic measurements of phase voltages to ground and of arc current were made at the time of the fault. Magnetic type oscillographs were employed for all measurements of current and voltage, with the aid of a shunt for measuring arc current, and water hose resistance potentiometers, previously described in Section II, for measuring voltages to ground. Surge-voltage recorders were connected to the three phases at the generating end and at the open end of the transmission line to supplement the oscillographic measurements of voltage. These surge recorders were calibrated with high-voltage impulses supplied by the lightning generator. Conditions which were varied included the length of line, as shown in Fig. 11, transformer connections, and the use of several neutral impedances, as indicated in Table I, and the location of the fault.

TABLE I—SUMMARY OF MAXIMUM AND AVERAGE OVERVOLTAGES ON SOUND PHASES FOR VARIOUS INDICATED SETUPS

					Maximum[2] overvoltage[1] (times normal)					Average[3] overvoltage[1] Measured by oscillographs			
		Transformer connections at Croton			From max. surge-recorder reading	Measured by oscillographs							
						At Croton		At Walker		At Croton		At Walker	
Length of line (miles)	Fault location	75 kv.	Neutral impedance (ohms)	Number of tests in each setup		Phase *T*	Phase *B*	Phase *T*	Phase *B*	Phase *T*	Phase *B*	Phase *T*	Phase *B*
1.5	Croton	(5)Y Y	Isolated	3	2.3	2.1	2.6			2.0	2.4		
16.5	"	"	"	6	2.1	2.5	2.6			1.9	2.2		
28	"	"	"	8	2.9	2.1	2.6			2.0	2.4		
37	"	"	"	11	1.8	2.3	2.4	2.3	2.5	2.1	2.2	2.1	2.3
37	Walker	"	"	4	1.4		2.1	2.1	2.4			2.0	2.3
37	Croton	"	"	2[4]	1.4		2.2	1.9	2.1		2.2		
37	Walker	"	"	2[4]	1.4		2.1	2.1	2.5		1.9	1.9	2.3
28	Croton	Y Y	"	4	2.5	2.1	2.2			1.9	2.1		
28	"	Δ Δ	"	4	2.5	2.1	2.3			2.1	2.3		
37	"	"	"	5	2.1	2.1	2.5			2.0	2.2		
94	Croton	Δ Δ	"	3	2.7	2.3	2.5	2.2	2.4	2.3	2.5	1.9	2.3
"	Walker	"	"	2	2.8	2.3	2.6	2.2	2.6	2.3	2.5	2.2	2.5
"	Stronach	"	"	2	2.8	2.4	2.7	2.5	2.7	2.4	2.6		
134	Croton	"	"	3	2.8	2.5	2.6	2.5	2.6	2.5	2.5	2.5	2.5
"	Walker	"	"	2	3.0	2.4	2.7	2.5	2.6				
"	Stronach	"	"	2	2.9	2.4	2.8	2.3	2.5	2.2	2.7		
37	Croton	(5)Y Y(6)	0	2	1.0	2.8	1.9			2.5	1.9		
"	"	"	1800/0°	2	1.0	2.2	1.6			2.2	1.6		
"	"	"	3350/73°	2	1.5		2.1				1.9		
"	"	"	6070/54°	3	1.9		2.1				2.0		
"	"	Δ Y(6)	3350/73°	2	1.6		1.6				1.5		
"	"	"	6070/54°	4	1.8		2.1				2.1		

Notes:

1. "Overvoltage" is expressed as a ratio of maximum peak during fault to normal peak just previous to fault.
2. "Maximum overvoltage" refers to highest voltage recorded for all tests in each setup.
3. "Average overvoltage" refers to the average of the maximum voltages for all similar tests of each setup.
4. For these tests 75-kv. aluminum cell lightning arresters were connected to each phase at Croton.
5. Low-voltage neutral grounded solidly.
6. High-voltage neutral grounded through impedance

Magnitude of Recorded Overvoltages. It can be seen from Table I that the highest sound phase overvoltage recorded by the oscillographs in the 63 arcing ground tests on the isolated system was 2.8 times normal, and that the maximum surge-recorder measurement was 3.0 times normal. The faulted phase voltage in no case exceeded the sound phase voltages. In no case were the surge-recorder measurements more than 15 per cent higher than the corresponding oscillographic records. Inasmuch as the surge recorder is inherently a less accurate instrument than the oscillograph, its measurements are chiefly valuable as a check on the order of magnitude of the oscillographic measurements, and as assurance that no high magnitude transients were missed by the latter. The maximum values of voltage from transformer neutral to ground recorded for the arcing ground tests on the longer lengths of 75-kv. isolated systems, ranged from 42 to 135 kv. (peak).

Nature of the Transient. Fig. 12, which shows the beginning and end of the fault for test 79, illustrates the nature of the transient changes at the point of fault as they took place in a large number of the tests. For this test an arcing ground was produced with a swinging wire on phase *M* at Croton, the 37-mile line being connected and energized through Δ-Δ transformers.

An analysis of faulted phase voltage indicates that at the fault location the voltage is reduced from the normal value of the 30-cycle wave just before the fault, to zero just after the fault starts. A traveling wave condition is set up, which becomes a standing wave as it is maintained for a short period of time by successive reflections back and forth from the open ends of the line to the grounded point. This standing wave is evidenced by damped oscillations in the wave of arc current and by similar oscillations in the voltage wave recorded at the open end of the line. An inspection of the transient oscillations in oscillograms 82-*A* and 82-*C*, shown in Fig. 12, illustrates this point. Oscillogram 82-*A* was taken at the fault location (Croton) while 82-*C* shows the voltages at one open end of the 94-mile line. When the fault was located at one end or the other of a single line system which was varied in length up to 94 miles, other oscillograms showed that the frequency of these oscillations (called oscillatory frequency) corresponded to the free or natural period of oscillation of the line. In the tests on the 94- and 134-mile lines, arcs at Croton resulted in arc currents of quite complicated wave shape due to the several frequencies produced by the unequal lengths of line from Croton to the ends.

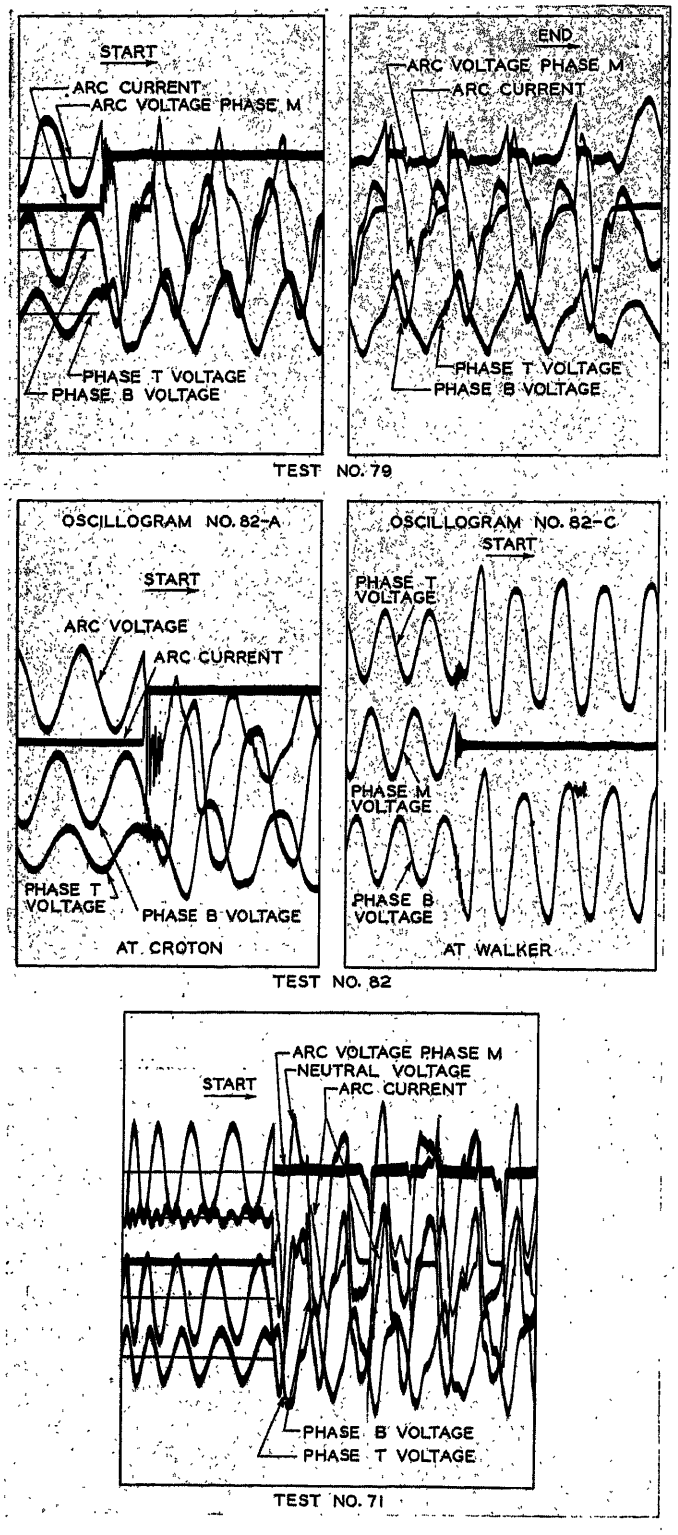


Fig. 12—Typical Oscillograms of Arcing Ground Tests

It can be seen in test 82 shown in Fig. 12, that the standing wave oscillations on the faulted conductor are accompanied by similar oscillations of relatively low amplitude in the voltage waves of the sound phases B and T. It is possible that these small voltage oscillations are caused by the oscillations in the faulted phase current or voltage, and not by reflection of a traveling wave initiated by a sudden change in the sound phase voltages themselves. Their small amplitude is apparently due to a low mutual coupling between phases and to the relatively high impedance at oscillatory frequency offered by the transformer windings, through which very little of the wave can be propagated. The barely noticeable oscillations do not occur at the highest crest of the sound phase voltage waves and add nothing to their maximum values. After undergoing shifts in phase relations, these voltages reach their crest values as waves of fundamental frequency on which a small d-c. transient, which shifts the zero of the normal frequency wave, is superimposed. A noticeable third harmonic voltage appears in the sound phase voltage during the fault.

In the majority of the tests the maximum overvoltage occurred during the first cycle of the fault, and was from 10 to 15 per cent higher on phase B than on phase T. Assume that the fault occurs on phase M when the voltage is at its peak value. As a result of the order of phase rotation $B\ M\ T$, V_B is advanced and V_T retarded about 30 deg. in their phase relations, at the instant V_M falls to zero. V_B, which at that instant is increasing in magnitude, is thus hastened to its crest value; while V_T, which has just passed its crest, is sent through a reverse curve because of its retardation in phase. It is probable that this difference in the behavior of V_B and V_T, when the fault occurs, accounts for the rather consistent superiority of V_B in the magnitude of its first cycle overvoltage.

Unstable Arcing Ground. The oscillogram for test 71, shown in Fig. 12, represents conditions during one of the most unstable arcing grounds that was produced. In this case the current usually restruck from zero once every half cycle, which is typical of a condition often assumed in constructing a theory for high arcing ground overvoltages. The high-frequency voltage oscillations are again very small, however, and the maximum sound phase overvoltage for this test, as recorded by the oscillograph and surge recorders, was respectively 2.4 and 2.6 times normal. It is furthermore assumed in theories that an unstable arc waits each time to restrike until the voltage across it attains successively higher values. Oscillogram 71 showed that the arc restruck when the voltage was equal to or less than its normal crest value and in most of the tests the restriking took place at less than normal crest voltage.

Effect of Length of System on Overvoltages. As the length of the isolated system was increased, there was a gradual, though quite definite trend toward higher overvoltages due to arcing grounds. This can be seen from the curves of maximum and average overvoltages shown in Fig. 13, in which the average overvoltage on phase T with a 134-mile line is 28 per cent higher than that for a 16.5-mile line. The data for these curves were selected considering only the system length, and neglecting the effects of other variables.

Effect of Point on the Wave of Faulted Phase Voltage Where Arc Strikes. There were 46 arcing ground tests with the neutral isolated in which the point on the wave of faulted phase voltage where the arc struck could be determined. For these tests the point of striking varied from 15 to 160 deg. In the majority of tests the arc struck in the portion of the cycle between 45 and 90 deg., but there appears to be no definite relation between the magnitude of overvoltage and the point on the wave where the arc strikes.

For most of the tests in which the arc struck between 100 and 160 deg. the overvoltages are all greater than 2.5. However, the majority of these tests were made on the 94- and 134-mile systems. The fact that the maximum overvoltages were recorded for these tests may be due either to the increased length of system or to the point on the voltage wave where the arc struck.

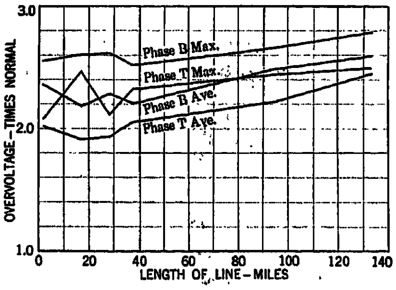


Fig. 13—Effect of Length of Line on Recorded Overvoltages Due to Arcing Grounds on Phase M 76-Kv. Isolated-Neutral System

Effect of Type of Fault. The various types of arcing ground faults investigated may be classified as arcs formed through high external resistance, and those formed through low resistance. It was found that a high-resistance ground fault, such as an intermittent tree ground, even if it persists for some time, produces a negligible rise in voltage on the sound phases. It is, therefore, concluded from these tests that an arc to a low-resistance ground, which allows maximum fault current to flow when the arc resistance is low, is more conducive to overvoltages than one to a high-resistance ground.

Effects of Other Changes in System Conditions. No important changes in the magnitude or nature of the overvoltages could be detected for different transformer connections, different locations of measuring equipment, whether at the source or the open end of the line, or for the few tests which were made on a short line when lightning arresters were connected to the system at Croton.

Overvoltages with System Neutral Grounded Through an Impedance. The essential results of the tests made with a neutral impedance can be found in the lower six lines of Table I. With the exception of two tests made with the neutral grounded solidly, in which the sound phase voltage was raised considerably higher than the normal value by an exaggerated third harmonic, the maximum voltages recorded during the tests varied from 1.6 to 2.2 times normal. These are somewhat less than the maximum values obtained with the system neutral isolated. Due to the fact that dangerous overvoltages were not developed in the tests under the isolated conditions, however, it is impossible from these tests to evaluate the minor changes resulting from the insertion of impedance in the neutral connection to ground.

Existing Theories of Arcing Ground Overvoltages. In general, three theories have been proposed to explain the development of the supposed overvoltages resulting from an arcing ground on an isolated system. These theories have been reviewed by others[4,5] and will not be discussed here. They may be briefly differentiated according to important assumptions made, that is, (1) both extinguishing and restriking of the arc controlled by oscillatory high frequency; (2) arc extinguishing controlled by oscillatory frequency and restriking by normal frequency; and (3) both extinguishing and restriking controlled by normal frequency. In all of these theories the maximum overvoltage occurs on a sound phase when its voltage is at the peak of a transient oscillation occasioned by the restriking of the arc, and can attain respective values of 19, 7.5, or 3.5 times normal neglecting damping. If factors for damping, leakage, and mutual capacitance are assumed, the maximum overvoltage for the second theory is about 5.5 times normal.

Analysis of Results of Tests from Standpoint of Above Theories. 1. In all the tests of this investigation, the oscillograms showed the striking and extinguishing of the arc to take place according to normal (30-cycle) frequency, in accordance with the third theory. This fact automatically prevents the tests from supporting the first two theories, since in both of these theories, the assumption is made that the arc is extinguished while the arc current is going through zero in an oscillation. This conclusion was also reached by Messrs. Peters and Slepian in their laboratory tests.

2. At the striking or restriking of the arc, the two sound phase voltages take their new value after going through an oscillation, the magnitude of which is only a very small fraction of the normal frequency peak of the wave. In no case was the magnitude of the maximum overvoltage affected by the amplitude of the oscillation. In this respect the tests fail to substantiate any of the theories.

3. If, in the normal frequency theory, a damping factor is taken into account, which damps the oscillation

in the sound phase voltage, the character of the phenomenon as observed in these tests agrees in certain respects with the normal frequency theory.

Conclusions from Arcing Ground Tests. The tests indicate that for the range of conditions investigated on this isolated neutral transmission system, faults involving arcs to ground produce overvoltages which may be characterized as follows:

1. The maximum overvoltage is approximately 3.0 times normal peak voltage from line to ground, and occurs on a sound phase, most frequently during the first cycle of the fault.

2. The overvoltage is essentially a fundamental frequency phenomenon, and is made up of the following components: A change in the impressed voltage from that of line to neutral to that of line to line without going through an oscillation of appreciable amplitude, a d-c. transient of several cycles duration which shifts the zero of the normal frequency wave, and in some cases a harmonic of lower order. Oscillograms showed that high frequencies within the range of the magnetic oscillograph did not affect the magnitude of the maximum overvoltage, while surge recorders testified that no higher magnitude transients were present.

3. Variations in the transmission system and in the test conditions which could be made with equipment available did not change the nature of the overvoltages, and caused changes in their magnitude of not more than 28 per cent. Conditions which were varied are as follows:

    Length of system (1.5 to 134 miles).
    Point on wave of voltage where arc strikes.
    Transformer connections (delta and star, see Table I).
    Fault location (at end or middle of line)
    Method of starting arc (fuse, swinging wire, etc.).

4. An arc to a high-resistance ground limits the shift of the system neutral and hence tends to reduce the magnitude of overvoltages produced.

5. At the striking of the arc, a highly damped standing wave follows the traveling wave set up on the faulted conductor. The frequency of the resulting oscillation is determined by the distance from the arc to the ends of the line.

ACKNOWLEDGMENTS

The authors wish to acknowledge the cooperation of Messrs. K. B. McEachron and J. G. Hemstreet in arranging the general conduct of the tests. They also wish to acknowledge the personal assistance of Messrs. E. J. Wade, W. J. Rudge, and M. F. Beavers of the General Electric Company, who aided in the impulse and arcing ground tests, and of Messrs. C. C. Tanner, F. D. Blackwell, D. E. Hackett and others of the Consumers Power Company, who took part in all tests.

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Discussion

J. K. Peck: As a supplement to the tests which were made at Croton, Michigan, in the study of overvoltages due to arcing grounds, which have been described in the paper by Messrs. Eaton, Dunham and myself, an automatic oscillograph was installed this year on the 140-kv. 60-cycle system of the Consumers Power Company at its Blackstone substation, which is located at Jackson. This oscillograph is a three-element string type instrument. It is connected through potential transformers to record phase-to-ground voltages, and is operated by residual voltage to begin operation within one-half cycle of the start of a disturbance on the system. The date and time of occurrence of the fault are recorded automatically by a camera which photographs a clock.

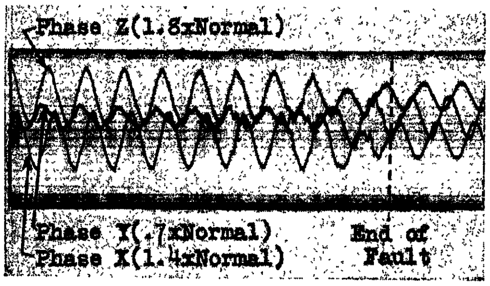

FIG. 1—FAULT ON 140-KV. ISOLATED SYSTEM VOLTAGES AT BLACKSTONE

At the present time this 140-kv. system, which operates with its neutral isolated, usually has a connected length of about 670 miles, and is fed by a generating capacity of from 150,000 to 170,000 kva. It would therefore seem to offer good possibilities for the development of overvoltages at the time of arcs to ground on the system.

Between March 1st and May 23rd there were 18 oscillograph operations at the time of disturbances on the system, most of which resulted from insulator arcovers. The highest overvoltage recorded by the oscillograph during each of these faults varied from 1.2 to 2.6 times normal peak voltage to ground. The duration of the faults ranged from 4 to 112 cycles. In most of these oscillograms evidences of arcing were observed in several cycles just prior to clearance of the fault, but in no case did cumulative oscillations appear in the voltages during the fault.

The oscillogram shown in Fig. 1. is typical of a number of operations. This particular fault, lasting for 32 cycles, was an arc to ground at the time of a lightning storm occurring on May 18th. The final 10 cycles of the disturbance are shown here, with 2 cycles of succeeding normal conditions. The first 22 cycles of the oscillogram exhibited no marked difference from the waves which appear at the beginning of this figure. Evidence of arcing is seen in the last 6 cycles of the fault in all phase voltages. There is, however, no building up of voltage. The maximum voltage to ground was 2.0 times normal on phase *Z* near the beginning of the fault, and gradually decreased to 1.8 times normal at the point shown.

In order to obtain still more complete data on this system at the time of disturbances, a three-phase automatic surge recorder is also being installed at the Blackstone 140-kv. substation. Records from this instrument should materially substantiate the automatic oscillograms, since the oscillograph cannot record transients which occur during the first half cycle of the fault, or surges of a very high frequency.

The nature of the phenomena and order of magnitude of the overvoltages recorded by the automatic oscillograph at the time of phase-to-ground faults, agree very well with the results of the experimental investigation at Croton, inasmuch as the magnitude of the maximum overvoltage was not affected by high frequencies within the range of the oscillograph, and was in all cases less than 3.0 times normal. Moreover, the system length and generating capacity for the 140-kv. system faults are considerably more than those which were available for the Croton tests, and thus these records from an operating system are a very valuable supplement to the tests described in the paper.

R. H. Park: In the tests described in the paper, it was found that the probability of a power arc resulting from an impulse flashover was increased when a capacitance load consisting of 35 miles of transmission line was connected in parallel with the point of flashover. Apparently this effect may be attributed to the discharge through the arc of the capacitative charge stored on the line. Thus in the tests the stored charge on the line had the effect of supplementing the charge stored in the lightning generator, and consequently causing a greater degree of initial ionization in the arc path, with a resultant greater likelihood of power arc follow-up. This is substantiated by the fact that in the case of tests made with parallel capacitance the power arc follow-up was found to be closely correlated with the point on the voltage wave at which flashover occurred, follow-up occurring most frequently when the flashover occurred at the maximum of the 30-cycle voltage wave. This effect would increase as the connected capacitance increased and in the case of long lines, or of an interconnected network of lines involving a large total length of transmission, might be very pronounced. It should be noted that this particular effect should depend on the connected miles of transmission line and should be independent of the connected generating capacity.

With regard to the method of measuring voltage, it might be well to point out that with a potentiometer resistance of 500,000 ohms the potentiometer itself may have an appreciable effect on the oscillations which develop during the arcing period, and it is possible that the presence of the potentiometer has prevented the occurrence of some of the phenomena which are under investigation.

J. M. Dunham: Mr. Park has suggested that the probability of a power arc follow-up resulting from an impulse flashover is increased when the connected capacity of the system is increased. Any effect which increases the ionization resulting from an impulse flashover will, other conditions remaining constant, increase the probability of power arc follow-up. There are several factors, however, which influence the effect of increased system length on the ionization of the arc path following an impulse flashover. Considering first the initial current due to the impulse flashover, and the initial current due to the discharge of the line capacitance through the arc path, it is evident that the influence on the ionized arc path of the discharge current may be great or small depending on the relative magnitudes of these initial currents. Another important factor to be considered is the duration of the discharge current compared with the duration of the impulse surge.

From the above it appears that a general statement regarding the effect of increasing the extent of a power system on the probability of a power arc resulting from a flashover, can not be made without qualification. It is unfortunate that because of the limitation of time and equipment more extensive tests could not be carried out at Croton to separate the various factors affecting power arc follow-up.

Mr. Park has brought up a very interesting point regarding the effect of the resistance potentiometers, used for measuring line voltages-to-ground, on the occurrence of overvoltage phenomena. Although, as stated in Section III of our paper the presence of a high damping factor would explain an agreement in certain respects between the normal frequency theory and the observed phenomena, the damping due to the resistance potentiometers cannot be considered as a high damping factor.

If the circuit conditions are simulated by a series circuit composed of the potentiometer resistance (R) from one phase wire to ground and the direct capacitance (C) of one phase wire to ground, the following formula can be used to determine the voltage on one of the unfaulted lines following arc extinction, expressed as a per cent of the initial voltage

$$E - E_o \, \epsilon \, \frac{t}{R\ C}$$

Calculations based on the preceding formula indicate that two cycles after the initial time the voltage on one of the unfaulted phases of the 135-mile system has decreased only 12 per cent due to leakage current through the potentiometer. For the 37.5-mile system the decrease in voltage after two cycles is 28 per cent. This leakage of charge, as evidenced by the calculated drop in voltage, was not sufficiently rapid to have prevented the building up, or at least an indication of the building up, of large voltages-to-ground on the unfaulted phases in accordance with any one of the three existing theories outlined in Section III of our paper.

Automatic Stations

ANNUAL REPORT OF THE COMMITTEE ON AUTOMATIC STATIONS*

CONSIDERABLE data on many phases of the automatic station art have been collected by subcommittees and are made part of this report, which is treated under headings as follows:

Technical Papers
Standards
New Subjects
Unfinished Business
Fire Protection
Wire Designations
Research
Operating Data
Telemetering
Bibliography

TECHNICAL PAPERS

The following papers are being presented under the auspices of the Committee at the Summer Convention, Asheville, N. C., 1931.

1. *A-C. Supervisory Control System.* By Othmar K. Marti.
2. *Supervisory Control for A-C. Electrified Railroads.* By C. P. West and H. C. Griffith.
3. *Automatic Combustion Control.* By C. H. Sanderson and E. B. Ricketts.
4. *Operating Experience with Automatic Stations.* By Garland Stamper and F. F. Ambuhl.
5. *Three Years' Operating Experience with Miniature Switchboard Supervisory Automatic Control.* By R. M. Stanley.

STANDARDS

Standards No. 26, Automatic Stations, has again been reviewed by the Committee. Recommendations for revisions in the list of device function numbers and in the table of minimum protection for power apparatus have been forwarded to the Standards Committee.

NEW SUBJECTS

Automatic combustion control and automatic alternating current networks have been studied this year by the Committee. A paper on Automatic Combustion Control, covering this subject extensively for the first time, is being presented at the annual convention.

UNFINISHED BUSINESS

Of the items listed last year, preliminary reports on Fire Protection, Load Dispatching and Wire Designations have been completed and are contained herein.

The following topics have been under consideration but no final reports have been rendered:

1. Economical Construction.
2. Noise Mitigation.
3. Automatic Alternating Current Networks.
4. General Telemetering.

SUBCOMMITTEE REPORTS

To the Subcommittees contributing the following reports generous acknowledgment is given. It is desired to make known that the efforts so prominently reflected in these reports are appreciated in full measure.

FIRE PROTECTION

Contributed by I. E. Moultrop and D. W. Taylor.

The methods of accomplishing suitable fire protection from the points of view of safety to personnel, safety to apparatus, and continuity of service have long been the subject of discussion and investigation by the electrical engineering profession. The size and importance of electrical installations make adequate fire protection a matter of utmost importance. The increasing use of automatically operated stations brings into prominence the special problems confronted by the designers of these usually unattended installations, which may in some instances be so far removed from the nearest aid in case of fire as to make automatic fire protection a corollary of automatic operation. It is the purpose of this report to point out some of these special problems.

When the subject of fire protection is considered, it is well to make a study of the causes of fires to obtain a perspective of the various elements entering into the problem. Consideration can then be given to design, and apparatus and material specifications, which will eliminate as much as possible the trouble at the source. Studies may be made to determine if oil circuit breakers have the necessary interrupting capacity; if all load carrying apparatus has the proper thermal capacity; if relay protection can be provided to clear short circuits before damage may occur, etc. Many apparatus characteristics, such as oil circuit breaker interrupting capacities, have been proven by tests so that greater reliability may be placed in their performance than was the case a few years ago.

Means to limit the fire to the vicinity of its source and prevent involving other apparatus in an attended or unattended substation, may take any one or more of

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*COMMITTEE ON AUTOMATIC STATIONS:
F. Zogbaum, Chairman,
Chester Lichtenberg, Secretary,
F. F. Ambuhl,
L. D. Bale,
C. W. Colvin,
A. M. Garrett,
Joseph Hellenthal,
C. A. Mayo,
I. E. Moultrop,
M. E. Reagan,
O. J. Rotty,
Garland Stamper,
D. W. Taylor,
L. J. Turley.

three forms, *viz.:* automatic means of fire detection and alarm; structural means of fire isolation; and means of fire fighting, either manual or automatic.

Automatic means of fire detection, as at present commercially developed, take the form of thermocouples and fusible links to convert the heat energy released by combustion into electrical energy, or of the more complicated apparatus working as a detector of the resultant smoke. Although these automatic means of fire detection have occasionally been installed in attended stations merely to alarm the operators, the recent mechanical improvement of the devices commercially obtainable for this service has resulted in considerable application of such devices in unattended stations to give alarm at some central attended installation and/or to operate fire-fighting equipment adjacent to the source of trouble. Unattended stations whose operations are reported to a central office through some means of supervisory control are particularly adapted for the installation of an alarm system between the station and the central office.

The second form of fire protection, structural means of fire isolation, is applied for the same reason and with equal effect in both attended and unattended stations. The large quantity of oil used in modern electrical apparatus makes fire isolation an important problem both indoors and outdoors. Generally, if possible, it is desirable to install large oil-filled apparatus outdoors and eliminate as much indoor oil-filled apparatus as is possible.

Indoors, apparatus of different types and different degrees of importance may be placed in different rooms, with fire doors between, either normally closed or closed by gravity upon the release of a fusible link. Some companies go so far as to install oil-immersed transformers in one room, large oil circuit breakers in a long narrow room with windows only at the ends, and oil-immersed voltage regulators in still another room; only the smaller breakers being installed in the same room with the switchboard and major bus structure. In connection with the location of windows, many stations are so arranged that any outdoor apparatus liable to catch fire, if installed adjacent to the building wall, are located at considerable distance from the nearest opening into the building. Another precaution taken as a means of indoor fire isolation comprises the use of cell doors and other trim made of treated wood or other fireproofed material. Current transformers, on which the relay protection is dependent, have been sometimes placed in separate compartments so they will not be involved in an arc from other equipment before they have actuated the tripping relays. Proper grounding of apparatus often lessens the chance of stray currents damaging other equipment during a short circuit. Elimination, as much as possible, of unprotected apparatus connected to the main bus is often desirable. Protection of apparatus, such as bus potential transformers, by means of resistance and fuses and careful isolation of bus arresters, should be considered.

Outdoors, transformers may be installed with fire walls between banks of two or three units or, if larger and more important transformers, between individual units. One company has recently adopted the policy, on large outdoor transformers, of eliminating the column-type oil gage from the conservator and of installing fuse-releasing gravity-closing valves on all connections between conservator and main tank. It is intended by this policy to prevent the spreading of possible transformer fires by the release of the large quantity of oil contained in the conservator, as sometimes happens through the cracking of the gage glass on the occurrence of fire in the immediately adjacent transformer and through the feeding out of burning oil from a rupture in the cover of a faulty transformer.

Both indoors and outdoors, fire isolation may be augmented by the installation of pits and drainage systems properly disposed with respect to oil-immersed transformers and regulators and oil circuit breakers.

The third form of fire protection, means of fighting the actual fire, divides naturally between the use of liquids and the use of gases. The most obvious liquid for this purpose is water, which is often piped to the end-bells of large rotating machinery and may be used elsewhere in connection with one of the commercial sprinkler systems; there is, however, considerable question as to the efficacy of water as a means of fighting oil fires. Other liquids take the form of special preparations, often generated on the premises at the time of fire, either by the mixture of two liquids or of water and a powder. Gaseous means are limited commercially to the use of carbon dioxide, which is heavier than oxygen and serves to smother the fire when applied in sufficient concentration; it is therefore particularly suitable in confined spaces where liquid might damage the apparatus and/or where the gases emanating from some of the commercial liquid preparations would be obnoxious. The efficacy of all these fire-fighting fluids may be considerably increased by the installation of permanent piping, designed to permit the direction of the fluid at the most advantageous point in case of fire. Whether or not the valves of this piping should be automatically operated depends not only upon the importance of the installation and the liability of a large fire, but also upon the proximity to a central attended installation and the attendant costs of automatic equipment for fire alarm as compared with the costs of automatic equipment for fire fighting in the unattended station.

It is believed that the art of fire protection is developing so rapidly, particularly in connection with unattended automatic stations, that no standards should be promulgated at this time by the American Institute of Electrical Engineers or others. It is thought that only by giving comparatively free rein can it be assured that progress will continue to be made in accordance with the best economic dictates.

The attached Appendix A is a preliminary attempt to classify for further investigation or study, I. the causes of fires, II. the spreading of fires, III. preventive measures, and IV. the extinguishing of fires.

Appendix A

I. Causes of Fires. II. Spreading of Fires. III. Preventive Measures. IV. Extinguishing of Fires.

I—Causes of Fires

A. Faulty Design
   1. Insufficient spacing.
   2. No allowance for temperature changes.
   3. Reduced clearances from distortion due to short circuits.
   4. Conductors or equipment improperly or insecurely supported.
   5. Weakness of mechanical structure or supports.
   6. Insufficient provision against heaving by frost, entrance of rain, or accumulation of sleet.
   7. Cannon construction (by cannon construction is meant the arrangement of barriers or compartments in such a manner as to direct an arc outward into other equipment or into operating aisles).

B. Faulty Equipment
   1. Improper design.
   2. Poor material.
   3. Defective materials or parts.
   4. Insufficient insulation, spacing of parts, strength or thermal capacity.
   5. Improper assembly.
   6. Improper and insufficient testing.
   7. Unnoticed failures as a result of testing.

C. Improper Application of Equipment
   1. Wrong material—moisture absorbing, subject to chemical change.
   2. Wrong apparatus—type, size, rating.

D. Aging of Apparatus and Material
   1. Deterioration of insulating material on conductors, supports, windings.
   2. Corrosion of metals from action of air, moisture, electrolysis.
   3. Effect of moisture, gases and corona in hastening deterioration.

E. Static Stresses
   1. Causing destruction of insulation.
   2. Collecting conducting material.

F. Magnetic Stresses
   1. Mechanical movement.
   2. Collecting conducting material.

G. Surges or Lightning
   1. Atmospheric conditions.
   2. Switching operations.
   3. Improper grounding.

H. Arcs (other than flashovers)
   1. Switching operations.
   2. Contactors.
   3. Commutators.

I. Exceeded Ratings
   1. Exceeded current rating, overload.
   2. Overvoltage.
   3. Exceeded temperature rating.
   4. Exceeded time.

J. Errors in Operation

K. Failure of Apparatus Containing Oil
(This includes oil circuit breakers, oil switches, transformers, potheads, etc.)
   1. Insufficient amount of oil.
   2. Surplus amount of oil.
   3. Slopping of oil (mufflers, discharges).
   4. Dripping of oil on other apparatus.
   5. Lowering of oil level due to leaks, syphoning or intense cold.
   6. Freezing of oil.
   7. Carbonization of oil.
   8. Presence of moisture.
   9. Explosions due to arcs following short circuits.
   10. Poor contact.
   11. Puncture of bushing.
   12. Internal corona discharges.
   13. Internal earth fault.
   14. Internal short circuit.
   15. Phase interruptions due to mechanical failures.
   16. Short-circuited laminations.

(Note: See other sections for failure of apparatus in general).

L. Exposure to External Attack
   1. Animals—birds, rats, nests, etc.
   2. Foreign material thrown on equipment—stones, kite strings, airplanes.

M. Dirty Apparatus
   1. Dirt from coal piles, or adjacent industries.
   2. Boring action of metallic slivers.
   3. Causing reduced radiation.
   4. Causing flashovers.

N. Spontaneous Combustion
   1. Oily waste or rags.
   2. Coal.

O. Friction
   1. Lack of lubrication.
   2. Improper alinement.
   3. Dirt.

P. Condensation
   1. Unheated conditions.
   2. Temperature changes in conduits.
   3. Unventilated conditions.
   4. Wrong materials.

Q. Heating Equipment and Piping
   1. Failure of electrical heaters.
   2. Defective flues.
   3. Explosions of oil burners.
   4. Escaping steam or water from pipes.
   5. Broken fuel lines.

R. Carelessness
   1. Improper tagging or operation (disconnects, etc.).
   2. Cigarettes, matches.

S. Atmoshperic Conditions
   1. Flashovers due to fogs, especially salt water fogs.
   2. Sleet or wind.

T. Exterior Fires
   1. Adjacent buildings.
   2. Grass and forest fires.

II—Spreading of Fires

A. Inflammable Material in Apparatus
   1. Insulating material in conductors, such as rubber and varnished cambric.
   2. Insulating supports or braces, such as wood.
   3. Oil or inflammable compounds.

B. Inflammable Material in Construction
   1. Wooden buildings, compartments, or structures.
   2. Forms used during construction.

C. Insufficient Segregation
   1. Insufficient barriers, compartments, cells or rooms.
   2. Insufficient spacing between types or classes of apparatus.
   3. Improper grouping of equipment, wiring, etc.
   4. Improper drainage of oil, etc.

D. Poor Housekeeping
   1. Rubbish during construction
   2. Accumulation of rubbish in operation.
   3. Storage of inflammable material.

E. Fanning Action of Ventilating Equipment.

F. Lack of fire Extinguishing Apparatus.

G. Failure to Announce Start of Fire, Smoke or Heat.

III—Preventive Measures

A. Use of fire-proof or fire-resisting material in construction.

B. Elimination of oil so far as possible.

C. Keeping premises and apparatus clean.

D. Segregation of apparatus.

E. Correct design or application.

F. Constant expert supervision.

G. Careful inspection before and during installation.

H. Periodic testing.

IV—Extinguishing of Fires

A. Detection.

B. Alarms.

C. Accessibility.

D. Automatic fire extinguishers—classification and suitability of each type.

E. Hand-operated extinguishers—classification and suitability of each type.

F. Drainage of burning oil.

WIRE DESIGNATIONS

Contributed by O. J. Rotty and M. E. Reagan.

The development of a uniform scheme of wire designations for station control wiring has been given some study with the idea that if a satisfactory scheme could be devised it should be offered for standardization.

The general use of such a scheme would produce uniform marking of control wiring at all stations regardless of whether the panels were wired by different manufacturers or by the user himself. This seems desirable for many reasons. The engineer laying out a new station or an extension to an old one would have to be familiar with only one scheme of wire designations and if the apparatus for a particular station was supplied by a number of manufacturers the wire designations would be alike for all the apparatus, resulting in simplification of interconnecting wires and common circuits. These points are also of importance to the construction or installation men, to the testing men, maintenance men, trouble shooters, etc.

At present there are many schemes in use, with each manufacturer and many utilities and engineering organizations having their own schemes all of which are different although some may have certain features in common. There seem to be many reasons why each scheme is preferred by its sponsor and why other schemes are objectionable. However, it is felt that a scheme can be devised which will fulfill practically all requirements and overcome the more important objections. The standard scheme must be of a general nature and must be applicable to all kinds of stations; *viz.*, railway, Edison, mining, hydro, a-c. distribution, and even steam plants.

There is a number of points in the designation of wires on which there is fairly general agreement. These are briefly as follows: 1. The scheme should be simple, easily understood and applied and with few special cases or exceptions; 2. it should be flexible so as to permit of additions or changes to the control without completely revising the existing designations; 3. it should provide the "tie-in" with or reference between the actual wire and the diagrams (either the wiring diagram, the schematic diagram, or both); 4. the wire designations should appear on the schematic (or elementary) diagram.

It also seems desirable that certain other ideas be worked into the standard scheme, which are briefly as follows: 1. The wire designation should be made up of as few digits as possible; 2. it should not be a complicated combination of letters and numbers; 3. it should preferably have some significance as to the apparatus or panel the wire connects to, although this appears to be difficult to devise and very likely an arbitrary scheme will be finally adopted; 4. operating and control buses and circuits of the nature of buses should be included in the standard scheme.

This subject has been taken up by this committee only recently and the time has been insufficient for the development of a finished scheme. However, it is felt that the work should be continued by the succeeding committee.

Several closely allied subjects have presented themselves for investigation but lack of time has prevented work upon them. They are: 1 Wire group or conduit designations or numbers, and 2, wire color codes. It is felt that these should also be given some study with a view to suggesting standards for them.

RESEARCH

Contributed by M. E. Reagan.

Research items to be studied and followed by the committee are divided under four main divisions. One object of investigation is to assemble data on operation while another object is to establish the trend of automatic expansion in operation. For instance, in the use of vacuum gas filled tubes in power and control systems, it will be the function of this committee to carefully record the various applications and keep experience charts showing the growth of usefulness and their performance.

The four general classifications are as follows:

I. Automatic Control of Rotating Machines (including mercury arc rectifiers).
    a. Synchronous converters.
    b. Motor-generator sets.
    c. Mercury-arc rectifiers.
    d. Hydro-electric generators.
    e. Frequency-changers.
    f. Synchronous condensers.
    g. Balancer sets.
    h. Battery chargers
        1. Automatic end cell switches.
II. Automatic Control of Static Machines.
    a. A-c. transformer substations.
    b. Periodic reclosing feeders.
    c. Static condensers.
III. Network Protectors.
IV. Supervisory Control.
    a. Terminal apparatus.
    b. Channels.
        1. Fused lines.
        2. Private.
        3. Carrier, etc.

Suggested Items.
  a. Curve of total installations by years.
  b. Curve of total kva. by years.
  c. Curve of per cent automatic to manual installation by years.
  d. Curve showing rehabilitation of old units for automatic service.
  e. Curve showing per cent availability by years.
  f. Data on primary causes of outages, such as
      1. Line trouble.
      2. Main apparatus trouble.
      3. Control trouble.
      4. Due to testers or maintenance man.
  g. Performance data on fuses in control circuits.
  h. Ventilation as it affects "sweating" of apparatus.
  i. General field testing of equipment expand last year's report
  j. Data on vacuum tube applications of all types in control work

TELEMETERING IN CONNECTION WITH LOAD DISPATCHING

Contributed by A. M. Garrett and J. J. Samson.

In order that electrical systems, particularly those of the public utility and traction companies, function with the highest degree of service standard and efficiency, it is necessary that the control of certain system operations be centralized.

Such operating knowledge and duties as restoration of the service to normal during or following a case of system trouble; the interchange of energy between systems or parts of the same system; switching in and out of service of generating station or substation units in accordance with load demands; the load quantities existing in different parts of the system; the maintenance of proper voltage, frequency, temperature of equipment; adjusting the system to take care of construction work in connection with system extensions, maintenance and repairs, are some of the functions that must come under the guidance of this group.

The majority of these functions is under the control of the load dispatcher or system operator who depends upon his knowledge of the operating condition of the system through the forces which actually operate it. This information comes to him in the nature of a periodic check, generally by telephone.

In recent years as the system developed through growth and expansion, and in some instances through combination, the problems associated with the handling of these systems become more involved, so that the need for quicker and more accurate information as to the operating status of the system became apparent. In order to handle the situation intelligently, a continuous record or "running account" so to speak was needed instead of a periodic sampling of conditions. To meet these requirements telemetering or remote indication equipment has been developed and placed in service in many systems in this country in the past five years. To take care of these problems under the old method would mean quite a material increase in the load dispatchers' force.

Telemetering is a means of transmitting to a central control point over a communicating circuit or special conductors, information necessary for the operation of the equipment, station or system. This may be electrical quantities (volts, amperes, watts, power factor), temperature, position of breakers, regulators, or any other information that it may be desired to obtain from the system.

It consists essentially of a transmitter at the remote end connected to the equipment from which information is desired, a receiver at the control end and the connecting circuit. The quantity of energy to be measured or position of equipment to be indicated is converted to a voltage and current (suitable for telephone cable) whose value is proportional and is transmitted to the receiver which is calibrated to record the information.

With a view to determining the trend of telemetering devices and methods, the committee decided that a survey in the form of a questionnaire should be made of those companies now operating this class of equipment.

The questionnaire covered the following points:

1. What of the following do you use telemetering for?
    Totalizing load.
    Current and voltage conditions.
    Temperature of equipment.
    Position of switch gear.
    Tap changer and regulator positions.
    Uses other than above.
2. State briefly the type of system and the principles of operation.
3. What channels are used?
    Telephone lines.
    Transmission lines.
    Special conductors.
   State approximate distances of transmission.
4. Is this system of aid in load dispatching?
   In what manner?
5. What criticism do you have of telemetering?
6. What, in your opinion, is the trend of development?

The term "load dispatching" is understood to cover broadly the function of load control and switching operation which is dependent upon telemetering information.

This survey has just been completed and a total of 35 companies canvassed. The following information has been compiled:

Under uses or application we found approximately 40 per cent of the companies use the equipment for determination of current and voltage conditions, while 22 per cent of the installations were for totalizing load and 18 per cent were for position indication of equipment.

Under types used, there seems to be a general use of direct current either in the form of balanced current or rectified current.

As the connecting circuit between the remote end and the receiving end, about 30 per cent used active telephone circuits, while the remaining 60 per cent used special conductors. The distance of transmission varies from 500 feet to 15 miles with no special average.

In answer to the direct question of whether the system was an aid in load dispatching, 60 per cent stated that it was, while the rest of the replies gave no opinion or indicated lack of experience due to the short time the equipment had been in service.

In reply to the inquiry on criticism of the equipment, the survey showed little or no adverse expression. One point emphasized was the lack of high speed response with accuracy comparable to the usual line of switchboard indicating instruments. There is a tendency where high speed is desired to sacrifice somewhat the matter of accuracy. Another criticism was on the cost basis, the installed cost of the equipment running into "considerable money." Especially is this true where special conductors are required over long transmitting distances.

Improvements toward simplification of the present complicated equipment, as means to greater reliability, was offered as one criticism.

On trend of development, practically all replies indicated a favorable reaction to future development, especially where extension to the system was in prospect. This applies particularly to the situation where interconnection is concerned. One reply mentioned there would be no future development for telemetering in this company as the type of distribution was being changed to an a-c. network whereby the substation would be eliminated.

In general, it can be stated that telemetering has established itself, and with extension of load control and switching operations made necessary through an increase in the size of systems, in interconnection between systems, and constantly increasing number of unattended stations, telemetering is proving a distinct aid in the solution of those problems of handling and operating an electric system.

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Communication

ANNUAL REPORT OF THE COMMITTEE ON COMMUNICATION*

IN accordance with the usual practise, this committee submits herewith a brief review of the developments during 1930 in electrical communication.

TELEPHONE SERVICE IMPROVEMENTS

Telephone service was improved during the year by the application of new developments and methods and improved maintenance. The average time to complete toll calls was lowered by 12 seconds to an average of one minute. Improved maintenance methods have reduced the frequency of troubles affecting subscribers' lines so that a trouble now occurs on the average but once in 22 months, a reduction in trouble frequency of about 11 per cent as compared with 1929.

Steady advancement in the quality of speech transmission was accomplished. On the longer haul toll business, unsatisfactory transmission conditions were experienced on only 1.5 per cent of the messages, compared with 1.7 per cent in 1929. One of the important factors contributing to this improvement was the institution of a more effective method for controlling the amplification of speech on toll calls involving two or more long circuits. An improved general plan for the design and rearrangement of plant to handle calls between remote points not connected by direct circuits was adopted. Under this plan, the number of intermediate switches is minimized with a consequent improvement in speed, accuracy, directness of routing, and transmission. A paper describing this plan, by Mr. H. S. Osborne, was presented at the 1930 Summer Convention. (A. I. E. E. TRANS., October 1930.)

SUBSCRIBER'S EQUIPMENT AND SERVICES

During 1930 the number of hand telephone sets in service increased to approximately 2,000,000 as against about 1,000,000 at the beginning of the year. The development of a type of hand set which would meet the electric and acoustic requirements of telephone practise in this country has involved the solution of difficult technical problems. These problems have been concerned primarily with the suppression of singing, for which the hand set has a tendency because of the rigid connection of the transmitter and receiver, and with the efficient operation of the transmitter in a wide range of angular positions. These difficulties have been successfully overcome through the application of a large amount of scientific work in the design of the hand set handle, the transmitting and receiving elements, and the electrical circuit connecting them. These achievements have made it possible to use the hand set without any sacrifice in performance as compared with the desk stand set.

For subscribers requiring a large number of attendants to take messages or orders, there has been made available an automatic call distributing arrangement associated with a simple type of attendant's position, whereby calls are immediately connected to idle attendants or, if none are available, are held and subsequently connected in the order in which they arrived.

A new type of private branch exchange suitable for larger residences and business offices of moderate size was made available during the year. No operator or attendant is required. Calls may be originated, answered, and transferred from any of the telephones. Intercommunicating calls are made by means of the dial. Complete privacy for both outside and intercommunicating connections is provided.

While arrangements have been available for some time for private branch exchanges whereby a number of telephones could be connected together simultaneously in a conference connection, these arrangements have been extended during the past year so as to enable the interconnection of a larger number of stations and to include more than one trunk circuit out of the private branch exchange.

CENTRAL OFFICE SYSTEMS AND APPARATUS

During 1930 there was an increase of about 1,000,000 dial stations, bringing the total to approximately 5,565,000, or more than one-fourth of the total number of stations in this country. Besides the conversion to dial of additional portions of large cities, increasing use has been made of dial equipment in small communities where services requiring the assistance of operators can economically be handled from near-by centers.

Further extensions have been made in the mechanical tandem facilities used primarily for service between the larger areas and neighboring suburban points. Arrangements are now in service for automatically inserting voice repeaters when required on calls between the more distant points. Facilities are also included for completing calls to a variety of types of offices, either mechanically or by key sets at call distributing tandem positions. An installation of call announcer apparatus, described in last year's report, has been made in New York. The mechanical tandem also includes a trouble recorder which provides a continuous count of calls affected by various classes of irregularities and prints, by means of a teletypewriter, a complete record of the channels and equipment used by such calls.

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*COMMITTEE ON COMMUNICATION:

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The panel system has been provided with a new type of equipment known as the decoder for translating the digits dialed by the subscriber into the electrical information required for routing the call to various types of offices. Panel equipment in certain areas is also being arranged to permit subscribers to dial calls directly to distant zones which previously required the supervision of an operator because of the additional charges involved. The equipment is arranged to determine the number of message units corresponding to the charge to the zone in which the call terminates and to cause a corresponding number of operations of the message register.

Time announcement systems for use in the larger areas have been modified by the addition of facilities for the distribution of announcements over a trunk network, equipped with repeaters to insure adequate volume and quality, so that one operator may furnish time announcements for a network of offices.

An improved low-speed interrupter, utilizing mercury make and break contacts, has been developed for use in giving flashing signals to operators and in timing sequence operations. For producing tones used as signals to operators and subscribers, there has been developed an alternator which enables close control of the frequency, magnitude, and harmonic content of the tones. The field windings and the tone output windings of this alternator are formed on the stator, and the tone is produced by an unwound, toothed rotor which varies the magnetic flux in the tone windings.

Privacy apparatus was put into service during the year on nearly all of the intercontinental radio telephone circuits operated out of this country. By means of this apparatus the radio waves transmitting conversations are so modified in their characteristics that if listened to with an ordinary radio set, speech is not intelligible. At the receiving end this process is reversed and intelligible speech restored. While this does not guarantee complete secrecy, it does furnish a considerable degree of privacy and represents an important step in advance.

Another important toll equipment development was a new type of toll switchboard in which the use of smaller jacks makes possible a substantial increase in the number of trunks and toll lines appearing at each toll operator's position. Tandem positions are also provided through which an operator may secure access to any circuit not appearing in the toll line multiple at her position.

OUTSIDE PLANT CONSTRUCTION AND METHODS

To facilitate the placing of tape armored toll telephone cables, a method has been developed whereby the trenching, laying of the cable, and the filling of the trench are simultaneously accomplished in one operation. This method utilizes a tractor behind which are pulled the trailer supporting the cable reel, the plow, and the drag which fills in the trench. From the reel, the cable is threaded through a pipe which leads it to the trench at a point directly in back of the plow. Under ordinary conditions it has been practicable, on the average, to lay more than one mile of cable per day with one outfit, using this method.

A new method which utilizes a single tube sleeve has been developed for making joints in aerial line wire. A hand operated rolling tool compresses the sleeve onto the wire in such a way as to provide a joint with no greater electrical resistance than a corresponding length of line wire and with a tensile strength at least equal to that of the wire. This new joint is expected to avert the electrical troubles now experienced with open-wire joints of the twisted sleeve type.

An important step has been taken by the communication interests cooperating with other pole using utilities, and others connected with the pole industry, in arriving at uniform classification dimensions for wood poles of southern yellow pine, western red cedar, northern white cedar, and chestnut. This work was carried on by the American Standards Association. Standard fiber strengths lb. per sq. in. have been established as follows: 7,400 for southern yellow pine, 5,600 for western red cedar, 3,600 for northern white cedar, and 6,000 for chestnut. These values have been accepted and made American Standards.

Under the new classification, a pole of a given class designation will have approximately the same breaking load regardless of pole length and species of timber. The adoption of the new grouping by all users of wood poles is expected to result in economies in the production and stocking of poles. The problems introduced by joint use will also be simplified as both parties to the joint use agreement will be using the same classification, whereas in the past this was seldom the case. Cost comparisons between the various species can be more easily made under the new classifications as prices may be directly compared class for class, whereas under the old tables calculations had to be made to determine the class of equivalent poles of other species of timber.

LONG DISTANCE TOLL CABLES

About 5,000 miles of cable for toll use were added to the telephone system of this country in 1930, bringing the total toll cable mileage to approximately 24,000 miles. Including the toll cable network on the Pacific Coast, which is connected with the toll cable network of the rest of the country by several individual and widely separated open-wire toll routes, there are now 129 out of 176 cities of the country having populations of 50,000 or more connected directly into the toll cable network. The fourth telephone cable between Key West and Havana was completed in January 1931. The new cable is non-loaded and employs the recently developed paragutta insulation. It is equipped with carrier telephone apparatus which now provides three telephone message circuits, as well as one d-c. telegraph circuit. Provision has been made for the addition of other telephone circuits when needed. The telephone facilities now afforded by the single new cable are equal to those furnished by the three older cables in total. This gain in efficiency is brought about by improvements in the art of cable construction, including employment of paragutta, as well as advances in the application of carrier methods using high frequencies for multiplexing.

About 35,000 miles of telephone circuit are now being regularly utilized for radio program transmission service and almost 200 radio broadcasting stations receive programs from these chains of wire circuits. Heretofore practically all of this service has been furnished by means of open wires using voice-frequency channels. However, a new type of circuit for toll cables has recently been developed which permits of transmission over long distances without material distortion of a frequency range from 50 to 8,000 cycles, at the same time transmitting a volume range of about 40 db. (energy ratio 10,000 to 1). These characteristics are desirable for the satisfactory transmission of music where the frequency and volume range requirements are much greater than in the case of speech. This new type of cable circuit is loaded at 3,000-ft. intervals and special repeaters are placed at approximately 50-mile intervals. Associated with each repeater is an attenuation equalizer and a delay equalizer, which correct for the attenuation and delay differences at different frequencies. A paper on this subject, by Messrs. A. B. Clark and C. W. Green, was presented at the 1930 Summer Convention (A. I. E. E. TRANS., October 1930, p. 1514.)

CARRIER TELEPHONE AND TELEGRAPH

During 1930 about 160,000 channel miles of carrier telephone facilities and 400,000 channel miles of carrier telegraph facilities were installed in the United States. Recent improvements of carrier circuits involve improved transposition arrangements and the introduction of 8-in. spacing of wires in place of the 12-in. spacing. This latter development permits an increase in the number of facilities obtainable from a given number of wires on a pole line.

The operation of voice-frequency carrier telegraph over the channels of high-frequency carrier telephone systems has been successfully applied. For example, each of the three two-way channels of a carrier telephone system has been filled with 12 carrier telegraph channels. Such a pair of wires accommodates a duplex d-c. telegraph circuit, an ordinary two-way message telephone circuit and 36 duplex carrier telegraph channels which if multiplexed would afford means for the transmission of about 7,500 words per minute for the telegraph facilities alone.

A paper by Mr. E. I. Green, discussing the transmission characteristics of open-wire telephone lines, and a paper by Mr. L. T. Wilson, discussing telephone line insulators, were presented at the 1930 Summer Convention. (A. I. E. E. TRANS., October 1930.)

INTERCONTINENTAL TELEPHONY

Most notable of the advances made during 1930 in the intercontinental telephone field was the opening on April 3 of service to South America. This service is provided by a short-wave radio circuit operating between the transmitting and receiving stations at Lawrenceville and Netcong, New Jersey, and corresponding stations near Buenos Aires, Argentina. The ratio portion of this circuit is 5,300 miles in length and it is therefore, the longest circuit now operating from the North American continent. The transmission characteristics of this circuit are, however, somewhat better than those of the short-wave circuits between the United States and England, due principally to the fact that the transmission path of the South American circuit is further removed than is that of the North Atlantic circuit from the polar regions and the adverse influences of magnetic storms. Furthermore, the South American circuit, running nearly along the meridian, experiences a more uniform condition as to daylight or darkness. As a result of these factors, extreme variations in transmission, which form an important problem on the east- and west-bound radio circuits, are materially reduced on this circuit.

At Buenos Aires the radio circuit connects with wire and cable circuits to more than 325,000 telephones in the Argentine Republic, Chile, and Uruguay, including the cities of Santiago and Montevideo.

Another feature of interest during the year was the establishment of radio communication between the United States and Australia by way of London. At London the transatlantic circuits are connected to a London-Sydney short-wave radio circuit, which at Sydney connects in turn with the wire network of the Australian Telephone Administration. This combined circuit is approximately 14,000 miles in length.

Four papers, discussing transoceanic telephone service in its various aspects, were presented at the 1930 Winter Convention by Messrs. T. G. Miller, Ralph Bown, A. A. Oswald, and F. A. Cowan.

By the end of 1930, many parts of the world had been linked together by radio-telephone circuits in addition to those mentioned above. Most of these circuits have one end in Europe, far ends in such distant places as Brazil, Argentina, Australia, New Zealand, Siam, Indo-China, Java, and Algiers. Not all of these circuits are yet connected with the telephone systems at their terminals, and they do not all, therefore, possess to the same degree the universal accessibility and utility of those radiating from North America.

SHIP-TO-SHORE RADIO-TELEPHONE SYSTEMS

A novel type of ship-to-shore service was inaugurated in the middle of the year through the equipment with radio-telephone apparatus of a New York City fire-boat. This equipment is arranged to enable continuous two-way telephone service between the master of the fire-boat and his land headquarters when the boat is under way. By means of this close communication, it has been possible to coordinate the efforts of the land and marine fire forces more effectively. As a result of the demand for telephone service of this kind in important harbors, both for harbor craft and ocean-going vessels, plans have been made for opening to such service in 1931, radio-telephone stations at Los Angeles, San Francisco, Puget Sound, and New York.

Commercial telephone service between ships at sea and the telephone system of the United States was extended during 1930 so that this service is now available to five ships: the Leviathan, Majestic, Homeric, Olympic, and Belgenland. Several organizations are involved in the provision of this service: the International Marine Radio Company, a subsidiary of the International Telephone and Telegraph Company, the Marconi Company, and the American Telephone and Telegraph Company. The shore stations are operated by the American Telephone and Telegraph Company on this side and by the British Post Office on the European side. During 1930, construction of a new land station at Ocean Gate, New Jersey, to care for transmission from shore to ship was completed. As in all radio-telephone transmitting stations, the antennas at this new station have a marked directional characteristic, the transmitted waves in this case being directed so as to traverse the North Atlantic shipping lanes. Four different wavelengths are used for transmission, ranging between 17.5 and 63 meters. Generally speaking, reliable transmission has been obtainable at distances from New York up to about 1,000 miles, corresponding with two days' sail. While satisfactory talks have been made at distances of 2,500 miles or greater, transmission at such distances has not been uniformly good.

A paper by Messrs. William Wilson and Lloyd Espenschied, discussing radio-telephone service to ships at sea was presented at the Northeastern District Meeting in May 1930.

TELEGRAPHY

During 1930 all Western Union tickers handling New York Stock Exchange service in the United States were converted to the high-speed type. This permitted increasing the output of stock quotations from 300 to 500 characters per minute. In the field of telegraphic distribution of quotations and other market information, many improvements in apparatus and methods of operation were developed and applied during the year which resulted in a reduction of manual handling, greater output and extended operation into territory not heretofore reached, including quotation service to Cuba.

There has been a considerable expansion during the past year in the use of automatic quotation boards for electrically indicating market prices and this service has been extended to a number of other cities in addition to New York, where the first boards were installed.

Numerous additional installations have been made of concentration equipment for printing telegraph circuits. A description of the apparatus used for this purpose is contained in the paper entitled *A Printing Telegraph Concentrator* presented by Mr. W. B. Blanton at the Winter Convention in January 1931.

The Western Union Telegraph Company has developed a method whereby channels of a multiplex system circuit may be automatically repeated and extended individually over single wires by means of simplex printers to offices. Circuits from several offices using simplex printers may be grouped at a central point and combined into a multiplex circuit to a distant central office. This system will give many small offices direct outlets to the large centers which could not have been economically provided with previous methods.

During the year there was a marked increase in the tendency to employ, in place of direct current telegraph to outlying points superposed on telephone circuits, a method of operation which is called "two-path polar operation." This involves the use of independent one-way polar circuits for the two directions and affords improved service with a lower maintenance cost as compared to the usual polar duplex method.

Several methods of measuring the quality of telegraph transmission have been developed. One form of apparatus which has been found very effective both in the laboratory and the field was described by Mr. F. B. Bramhall in a paper entitled *Telegraph Transmission Testing Machine,* presented at the 1931 Winter Convention.

A paper describing various technical features in connection with the submarine high-speed duplex telegraph cable between Bay Roberts, Newfoundland and Horta, Azores was presented at the Winter Convention in 1931 by Messrs. J. W. Milnor and G. A. Randall. At the same convention, Mr. Milnor presented a paper on the influence of interference in submarine cables.

In addition to the statewide police teletypewriter systems in Connecticut and Pennsylvania, an extensive system of about 30 stations was installed last year in New Jersey for the New Jersey State Police. There is an increasing number of large city police networks, such as those of New York City, Boston, Buffalo, and St. Louis. The United States Coast Guard also has such a system in use along the New England Coast.

Progress has been made in the development of switchboards for teletypewriter service to permit the interconnection of these machines in a manner similar to that by which telephone instruments are interconnected.

A new type of belt conveyer has been developed by the Western Union Telegraph Company for carrying telegrams between the various parts of the central office. In this conveyer messages are carried along between a steel channel and a moving flat belt about 1¾ in. wide, the motion of the messages being due to their sliding along the steel channel with practically no friction while adhering quite firmly to the belt. The messages can be taken around vertical or horizontal turns as well as through vertical and horizontal twists.

MUNICIPAL AND PROTECTIVE SIGNALING

There has been a steady increase in the use of electrical traffic signals. In the larger cities there have been several installations of flexible progressive systems, while in smaller places and in outlying sections of the larger cities, the detached intersection type of signal is still largely used. For important intersections and through traffic highways, vehicle controlled signals have been fairly successful but are expensive to install and maintain, as compared with the predetermined period signals. Vehicle control of signals obtained otherwise than by switches imbedded in the street surface, such as light beam control, has been tried out.

There has been a considerable use of electrical caution flashers in place of earlier types employing compressed gas, and practically all new installations are electrical. More illuminated caution signs are being installed and cheaper methods of illumination than by the neon tube method are being investigated

An important development of the past year concerning municipal fire alarms, has been the production of signal boxes and central office control apparatus, making effective use of ground return to send in alarms at such times as the circuit is in abnormal condition. Previous attempts to accomplish this introduced some abnormal condition on an otherwise normal circuit. This defect has now been practically overcome, and signal boxes have been developed that will operate in the usual manner on a normal circuit while at the same time they will transmit signals over a grounded, short-circuited or broken circuit without the necessity of making any temporary alterations at the signal box. While this development is too recent to be able to judge of its effects, it may permit of more leeway in circuit construction than is now considered safe, such as the installation of both sides of a circuit in the same aerial cable. The importance of this improvement may be estimated when it is considered that fires often occur at times when circuit conditions are apt to be disturbed by storm, explosion, or accident.

The use of single battery with trickle charger in place of duplicate batteries charged alternately by motor-generators is increasing with consequent increase in battery life.

The use of rectifiers and floating batteries or of transformers and a-c. circuits in connection with institutional fire alarms has progressed to such an extent that practically all new installations make use of public electric supply for the operating current in preference to primary batteries or to storage batteries charged from motor-generators. The practise of connecting automatic sprinkler alarm valves to municipal fire alarm boxes so that an alarm will be sounded automatically for any appreciable flow of water, has spread.

Experiments have been made on improved flash-light mechanisms for calling patrolmen to signal boxes. One such system has been installed lately in Boston. This permits any citizen desiring to call a policeman to operate an exposed lever which starts the flash-lights blinking the number of the signal box from which the call is made.

TELEVISION

Further advance was made in television as an accessory of telephone conversations by the development of means whereby two people at a distance are enabled both to converse and to see one another as if seated face to face in the same room. One of the interesting problems encountered in this development was that of sufficiently illuminating the faces of the parties engaged so that their images could be transmitted without, at the same time, dazzling their eyes to such an extent that they would be unable to see before them the image of the other party. This difficulty is met by employing blue light for scanning the faces of the parties. While the eyes are relatively insensitive to this color, the photoelectric cells used to pick up the light reflected from the face and generate the television signals are highly sensitive to it. Concealed microphones and loud speakers connected by four-wire telephone circuits are used in place of conventional telephone instruments to provide the talking portion of the system. The problem of operating a loud speaker and a sensitive microphone in the same small booth in such a manner that a self-sustaining singing circuit would not be created has been solved by specially treating the walls of the booth to prevent the reflection of sounds into the transmitter and by so locating both transmitter and loud speaker that the transfer of sound between them is minimized. While the experimental system is only two miles long, the television apparatus will function satisfactorily over distances of hundreds of miles when connected by suitable circuits as was shown by the one-way demonstration between New York and Washington.

Three papers dealing with television, by Messrs. H. E. Ives, F. Gray, M. W. Baldwin, H. M. Stoller, D. G. Blattner, and L. G. Bostwick, were presented at the 1930 Summer Convention. (A. I. E. E. TRANS., Oct. 1930.)

AIRPLANE RADIO-TELEPHONY

Development of telephone communication with airplanes continues to progress, and it has been found to be of very great importance for communication between transport planes and ground stations. Two-way radio-telephone apparatus for communication between planes and ground has been developed and supplied for equipping a comparatively large number of planes. The value of such equipment may be indicated by the fact that legislation provides for increased revenue to air mail contractors flying planes equipped for two-way radio communication

Two papers on this subject were presented during the year, one by Mr. R. H. Freeman at the Pacific Coast Convention, the other by Mr. Eugene Sibley at the Middle Eastern District Meeting in October.

SYNCHRONIZING RADIO BROADCASTING STATIONS

There has been considerable experimental work carried on during the past year by the prominent radio organizations along the line of synchronizing broadcasting stations so that the same radio program may be broadcast from different stations operating at the same frequency. Best results are obtained only with a high degree of synchronism between the carrier frequencies of the different radio stations. In certain of the more successful experiments the control of the radio station frequencies has been carried out by sending over wire circuits standard frequencies of 4,000 or 5,000 cycles which, at the radio stations, are stepped up and used either directly to provide the radio carrier or indirectly to control the frequency of a local oscillator. While it is evident from the tests which were made that line circuits can be used very satisfactorily for transmitting control frequencies, certain requirements are imposed on the radio station frequency step-up equipment to iron out minor line fluctuations, which are, of course, greatly exaggerated when the frequency is raised from the relatively low frequency transmitted over the lines to the radio frequency of from 500 to 1,000 kilocycles.

STANDARDIZATION OF RADIO TERMS

During the past two years the Standardization Committee of the Institute of Radio Engineers has had under way a complete revision of definitions of terms, abbreviations, symbols, and methods of measurements and tests. A preliminary report of this work was issued in December, 1930.

FOREIGN COMMUNICATION MATTERS OF INTEREST

During the year international service was extended in Central America by the interconnection of Guatemala and El Salvador. In Mexico the subscribers of a second large network were given access to the United States and all points reached therefrom.

Conference toll service or multiple telephone service was established in the Netherlands. By means of this system from three to six subscribers in the same or different cities may be interconnected at the same time so that any one of the subscribers may be heard by all of the others.

Picture transmission service was extended in a number of countries, particularly in Japan.

In Europe the toll cable network was increased during the year by 6,000 to 8,000 kilometers. Two additional submarine cables were placed across the English Channel and one was placed between Sweden and Germany.

A complete rotary automatic exchange system was installed in Vatican City and connections were established with the international network.

Direct dialing over long distance telephone lines was successfully demonstrated in Europe and installations were made in several countries. Toll dialing has been employed in the United States to a limited extent for a number of years.

Transatlantic radio-telephone service was extended to include a number of new countries in Europe and to reach additional points in countries to which service had previously been given. Connections to points within the Arctic Circle became possible for the first time when transatlantic radio telephone service was extended to include all of Sweden.

During the year the International Telephone and Telegraph Corporation, in cooperation with the government administrations concerned, opened direct radiotelephone links connecting Buenos Aires with Paris, Berlin, and London. These additional links between South America and Europe not only decrease the use of long land lines formerly required to serve points distant from the radio terminal, but greatly increase the reliability of the international connections as a whole. When, because of atmospheric disturbances or for other reasons, one link is unable to give commercial service, the traffic may be routed over one of the other links. The question of allotting the traffic over the different circuits and adjusting rates so that the rate between two points will not depend upon the routing of the call has been by no means a simple one, but with the cooperation of the various government administrations much progress has been made.

Commercial service was made available between telephone subscribers in Chile, Uruguay, and Argentina, and subscribers in Belgium, Denmark, Switzerland, Austria, Lithuania, Poland, Esthonia, Norway, Sweden, Czechoslovakia, and Jugoslavia through one or another of the four direct links from Buenos Aires which, of course, also serve Spain, France, Germany, and Great Britain.

Commercial telephone service was opened to some of the Canadian National Railway express trains and equipment for the reception of broadcast programs on moving trains was provided in a number of countries, including Jugoslavia, Italy, and Austria.

During the year technical development work continued to prepare for improvements in existing apparatus and methods as well as to explore new fields, such as signaling and dialing over radio-telephone circuits, and the use of the so-called ultra short waves, those of under five meters.

COOPERATION BETWEEN WIRE USING COMPANIES

The many problems arising in coordinating the wire plants of the power and telephone companies led to the formation of the Joint General Committee of the National Electric Light Association and Bell Telephone System in 1921. Since that time an extensive program of investigation has been in progress and many important results of this work were published in 1930 as Volume 1 of Engineering Reports of the Joint Subcommittee on Development and Research. A review of the work of this subcommittee was given in a group of four papers presented at the 1931 Winter Convention as a symposium on the coordination of power and telephone plants.

During the last two or three years three other Joint General Committees have been organized with the general objective of working out methods of procedure for the coordination of wire plants. These are the Joint General Committee of the Western Union Telegraph Company and the National Electrical Light Association, the Joint General Committee of the American Railway Association and National Electric Light Association and the Joint General Committee of the American Railway Association and the Bell Telephone System. These committees are proceeding with the formation of the fundamental bases of procedure for the cooperative handling of mutual problems between the utilities concerned and the carrying out of such development and research work as appears to be necessary in connection with the problems involved.

APPLICATIONS OF PROBABILITY THEORY IN TELEPHONE PRACTISE

The importance of the probability theory and the related theory of statistics in telephone practise are, in a general way, well known by the engineering profession. However, a short résumé of the matter together with a brief statement of additional applications made during the last year may be welcome.

The oldest and best known application of the theory in the art of communication is its use in the determination of the loads which can be placed on various manual and dial trunking arrangements in order that efficient service be rendered. Unbalance effects on loaded circuits and other transmission lines of periodic structure also give rise to linear and other types of error function problems for the solution of which recourse to probability theory must be had.

The scheduling of adequate sampling plans for determining the quality of telephone equipment at various stages of its manufacture, after delivery to the operating companies and after installation, make heavy demands on probability and statistical theory. Within the last year extensive sampling schedules have been made for determining the extent to which the human factor in the telephone business is performing its assigned functions. For example, sampling theory is now being applied with reference to the performance of the repair clerk and test desk man, the quality of work done by installers and repairmen, the quality of subscribers' contacts in commercial offices and the quality of directory printing and delivery service.

Electric Welding

ANNUAL REPORT OF THE COMMITTEE ON ELECTRIC WELDING*

THIS report consists of two sections; the first dealing with the Organization and Policies, and the second with the Progress of the Art.

I. Organization and Policies

During its first three years, this newly created committee has gradually extended its field of action until the field overlapped that of various technical committees of the American Welding Society. It was necessary, therefore, to establish a clear understanding with the A. W. S. in order to create an exchange of information and to avoid duplication of effort. It became apparent that it would be more profitable to leave such problems as the metallurgy of the welding processes, methods of testing the completed welds and organization of the procedure control, to the committees of the A. W. S.

Our efforts have been concentrated, therefore, on sponsoring the advancement of the theory of the electric arc, the design of the electric welding apparatus and the use of electric welding processes in the manufacture of electrical machinery.

The gathering of all available information on the progress of the art and the presentation of these facts through the medium of our annual report to the whole membership of the Institute is another important function of this committee.

As the activities of our committee have increased, it was felt at the beginning of the present fiscal year that the time had come to organize several subcommittees composed of physicists and engineers especially interested in one of the above specific problems. The committee as a whole has been concerned with the general survey of the advance in the progress of the art.

The present organization of subcommittees is as follows:

Research (Phenomenon of the Electric Arc) Dr. S. Dushman, Chairman, Dr. J. Slepian, Mr. H. M. Hobart, Mr. W. Spraragen, Mr. A. M. Candy.

Electric Welding Machinery (Designs of) Prof. F. Creedy, Chairman, Mr. J. C. Lincoln, Mr. A. M. Candy, Mr. A. Churchward, Mr. H. M. Hobart, Mr. K. L. Hansen.

Resistance Welding. The subcommittee on Resistance Welding has only been partly organized with Mr. E. Lunn and Mr. H. W. Tobey gathering preliminary information.

Papers

Through the efforts of the members of our committee, a symposium on welding was presented during the Winter Convention of the Institute. A paper by Dr. G. M. Shrum and Mr. H. G. Wiest, Jr. was presented by Dr. S. Dushman which related to the new experiments of the phenomenon of the electric arc.

Three papers were presented by Mr. J. H. Blankenbuehler, Mr. S. R. Bergman and Professor F. Creedy on the subject of the design of electric welding generators.

Two papers by Mr. M. Thomson and Mr. S. Martin, Jr. were on the subject of the resistance welding as applied in the manufacture of electrical apparatus.

Another paper on the design of the electric welding generator was published in the Journal of the A. I. E. E. prior to the above Convention, by Mr. C. J. Holslag.

II. Progress of the Art

General

The past year was characterized, first, by an outstanding improvement in the quality of the welds produced by various methods, secondly, by the refinement in the design of electric welding equipment, and thirdly, by the unprecedented expansion in the use of the resistance welding process.

The methods of testing and the procedure control attained such refinements that the quality of the welds produced on pressure vessels can be checked with accuracy.

The most outstanding accomplishment in the field of application of the electric arc in the past year, is the fabrication of 24 all-welded steam boilers by the Babcock & Wilcox Company for the United States Navy for installation on the new scout cruisers.

In the past, the arc welded oil stills for high pressure were manufactured successfully for a number of years by the A. O. Smith Corp., yet it is the first time that high-pressure steam boilers were fabricated by the electric arc and installed on the fighting ships.

Improvement in the Quality of Arc Welds

Arc welding was introduced into general use in this country during the World war. The first attempts to adopt the European method of welding with heavily fluxed electrodes, did not meet with general approval. Instead, the technique of welding with bare wire electrodes was developed to such an extent that practically all the arc welding in this country was done, until recently, by that method.

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*Committee on Electric Welding:

P. P. Alexander, Chairman,
C. A. Adams,
A. M. Candy,
Alexander Churchward,
F. Creedy,
S. Dushman,
F. M. Farmer,
K. L. Hansen,
H. M. Hobart,
C. J. Holslag,
J. E. Kearns,
J. C. Lincoln,
Ernest Lunn,
B. T. Mottinger,
J. W. Owens,
J. Slepian,
William Spraragen,
H. W. Tobey.

Since the tensile strength of the welds produced with such electrodes is about the same as that made by the most expensive heavily fluxed electrodes of European make, for many applications the bare wire is entirely satisfactory. It should be noted, however, that both bare wire electrodes and heavily fluxed electrodes of European make produced welds lacking in ductility.

With the extension of the field of application of arc welding, it soon became apparent that for the use of arc welding on such structures as pressure vessels, electrodes of different types would be needed. Over ten years ago, work in this direction was started by the Electric Arc Cutting & Welding Co., Wilson Welder & Metals Co., and some other concerns and individual investigators, each of whom produced a new type of heavy or lightly covered electrode. These electrodes had certain advantages over the bare wire electrodes.

Decided advance in the improvement of the quality of the welds was made a few years ago by the General Electric Co. with the hydrogen gas shielding of the weld, by A. O. Smith Corp. with special wood pulp covered electrodes, and by several other individual investigators and concerns, each of whom developed in the last year or two, a very efficient type of fluxed electrode giving welds of high ductility, a quality which is absolutely essential for work on steam boilers and many other types of pressure vessels.

At the present time, several manufacturers of pressure vessels, in advertising their welds guarantee a ductility unheard of only a few years ago. The General Electric Co., A. O. Smith Corp., Blaw-Knox Co., Struthers-Wells Co., Kellog Company, Fusion Welding Corp., The Lincoln Electric Co., and Babcock & Wilcox Co. are probably only a part of the list of concerns now producing highly ductile welds. This advance in the quality of the produced welds opened new fields for arc welding, of which the steam boilers for the United States Navy is an outstanding example.

Resistance Welding

The welds produced by this process are of the highest quality with respect to strength, ductility and resistance to fatigue. The development, therefore, consisted mostly in the improvements in the design of the welding machines and application of such machines in new fields.

The most outstanding feature of the past year was the great development of welding pipes by the resistance process. Several machines up to 6,500 kva. each have been built for welding, by the flash welded process, longitudinal seams 40 ft. long. By the use of such machines, a weld 40 ft. long is produced simultaneously all along the seam and in less than one minute on pipe some 24 inches in diameter and of a plate up to ½ inch in thickness. Similar resistance welding machines of 1,200-kva. capacity weld circumferential seams of similar pipe. All the electrical parts for the above machines have been built by the Swift Electric Welder Company. A spot welder of 800 kva. with electrodes of 3½ inches in diameter, which probably is the largest machine ever built in this country, has been successfully built by the same Company for special heavy welding work.

Other concerns (amongst which the Thomson-Gibb Electric Welding Co. is the pioneer), developed the continuous method of seam welding. This last method had previously been used on a large scale for welding thin walled tubing. Within the last year, this method has been applied to the continuous seam welding of pipe of considerable diameter and wall thickness. At the present time, several manufacturing concerns are producing welded pipe up to 40 ft. long and it is expected that by butt welding two of such lengths in the factory, a pipe of 80 ft. long will be available for construction work.

This great development in the welding of industrial pipe by the resistance process was due to the decision of several large concerns to extend the pipe lines for transportation of natural gas and gasoline from the producing areas to the consuming districts over 1,000 miles away.

This development should be of especial interest to engineers since it indicates the possibility of transmission of power over longer distances by gas than have been accomplished by the electric current.

As was remarked by a well-known consulting engineer, the electrical engineer should rise to the occasion and surpass gas with respect to distance and amount of power transmitted. He has plenty of as yet undeveloped alternatives to the 60-cycle synchronous system as at present employed.

The resistance welding process is being further developed in the application to the automobile industry where it greatly outdistances all the other welding processes. Another important field of application of resistance welding is the manufacture of wire goods which comprises even such fields as the welding of wire netting for reinforced concrete. Machines making up to 24 welds simultaneously have been built and are in successful use. In the fabrication of electrical machinery, the resistance process has already been applied on a large scale to the manufacture of small transformer tanks. The application of this process has also extended to the fabrication of motor magnet frames.

Structural Steel Welding

In the field of structural steel, arc welding has already proved to be entirely satisfactory, and therefore, received further important applications. All arc welding of this type of construction is done with entire satisfaction with the bare wire electrodes.

Amongst the high buildings erected during the past year, (partly by welding and partly by riveting) are the buildings of the Southern California Edison Co., the Edison Electric & Illuminating Co. of Boston, and the DuPont Corporation at Wilmington, Delaware. The highest building entirely welded was erected by the Dallas Power & Light Co. This building has 19 stories and measures 246 feet above the foundations. The Westinghouse company erected several industrial and office buildings, all entirely welded. The highest of these buildings measures 190 feet above the foundations. It should be noted that in the erection of the buildings, only very few welding machines are necessary. In the erection of the 19 story building at Dallas, only four arc welding machines were used.

Shipbuilding

In the shipbuilding field, arc welding is being extended rapidly and all our shipbuilding companies such as the Newport News Shipbuilding & Drydock Co., The Bethlehem Shipbuilding Co., and many others as well as the U. S. Navy Yards, are using arc welding quite extensively for fabricating various internal structures on ships. On smaller ships, the electric arc has been used successfully even in welding the hulls.

The Electric Boat Company, at Croton, launched during the past year, an all welded barge, 118 ft. long, of Ewertz patented design. The Federal Shipbuilding & Drydock Co., at Curney, N. J., welded a number of barges, and the Standard Steel Shipbuilding Corp., of Los Angeles, completed an all-welded 65-ft. yacht.

The application of arc welding in shipbuilding requires a careful study of the design of the welds and the details of the technique of welding. The long welded seams characteristic in this type of construction may be subject to high internal stresses and therefore should be produced by the best known methods and electrodes. The amount of welding per ton of steel in shipbuilding is very much greater than in the erection of buildings where only the short welds are necessary. It may be expected that in the construction of barges and small vessels for internal navigation, arc welding will soon outdistance riveting.

Automatic Machines, Alloy Electrodes and Special Arc Torches

The design of automatic arc welding machines advanced still further and several concerns are now manufacturing either full automatic or semi-automatic machines of a very efficient design for use with metallic electrodes. The Lincoln Company made further improvements in automatic carbon arc welding machines which produce welds of high ductility, and the General Electric Company applied the atomic hydrogen process to automatic welding as well as for hand welding.

The development of special alloy electrodes for hand welding as illustrated by the Stoody process, made considerable progress. The surfacing of various parts of machines subject to wear and abrasion with hard surfaces in certain cases can be successfully accomplished.

The development of special torches for use of indirect arc (similar to the flaming arc) extended the field of arc welding to the low-melting-point alloys. A special torch developed by Hansen and utilizing the d-c. arc can now be used for brazing, soldering, and welding low-melting-point extruded alloys. Another torch utilizing the a-c. arc has also been put on the market by the Warner Co., of Los Angeles. It can be used successfully on light work of brazing, soldering, and welding steel sheets of light gage.

Design of Electric Arc Welding Generators

The advances and refinements in the design of the electric welding generators have been carefully followed by the subcommittee on Electric Welding Machinery, which reports as follows:

An outstanding feature of the year's work in the development of direct-current arc welding generators, is the attention which has been devoted to their transient characteristics. It has been realized that the momentary shortening of the arc produces a large momentary transient current, which tends to cause explosions or "sputterings" detrimental to welding. Means have, therefore, been sought by several workers by which these momentary transient currents may be eliminated and papers on the subject have been presented by Blankenbuehler, Bergman, Holslag and Creedy.

The direct-current welding generators contain a main exciting coil either shunt, separately excited, or a combination of the two, and a demagnetizing series circuit whose function is to reduce the voltage with increasing current. One important type of transient is caused by the voltage induced in the main exciting circuit by transformer action from the series demagnetizing circuit and this type of transient may be eliminated by reducing this voltage to a small value. There is no need to eliminate this voltage altogether because it is only necessary to reduce it to such a degree that the solutions of the differential equations which determine the current approximate to the logarithmic instead of the oscillatory type. Blankenbuehler discussed a machine with separately exciting coil and reverse series winding only, and injects into the separately excited circuit a voltage proportional to the current flowing through the reverse series winding (the welding current) by means of a series transformer. This voltage is opposite in direction to that induced in the same coil by the reverse series winding so that the two tend to cancel.

The machine treated by Bergman has two distinct poles whose flux cuts the conductors between positive and negative brushes. One has constant flux and the other is shunt excited from a third brush intermediate between the main brushes, armature reaction being relied upon to reduce its voltage with increasing current. In this case a series transformer is used to inject into this shunt circuit a voltage proportional to, but opposite in direction to that due to induction from the armature.

In Creedy's machine in which the effect of shunt and separately excited windings is produced by a single coil, no transformer is employed but the same result is produced by reducing the reluctance of the main magnetic circuit so that the number of turns on the main exciting coil is very much reduced and consequently the e. m. f. induced in it by the series demagnetizing circuit becomes small. With this latter device a neutralizing winding becomes necessary to avoid sparking and excessive reactance of the armature winding.

Testing of Welds

Several non-destructive methods of testing of welds have been developed among which the X-ray method is already being applied as a regular procedure control on welds made on important structures. The magnetic and the stethoscope methods are also available. It should be noted also that a series of experiments has been conducted with the gamma rays produced by radium emanation for testing of welds on heavy plates and steel castings.

Further Research

Since the electric arc is the foundation on which the entire arc welding industry has been built, our subcommittee on Research recommends further study of this phenomenon. The outlined problems are as follows:

1. Probe measurements in arcs between iron electrodes, using a technique somewhat similar to that adopted by Nottingham in his investigations on the arc between copper electrodes in air.
2. Arc characteristics should be taken as a function of the pressure for different gases, such as carbon dioxide, air, and argon.
3. The question of the part played by fluxes, or additions of various "dopes" to the welding rod.
4. Determinations of the energy consumption at the electrodes, using a calorimetric method.
5. Accurate determination of cathode drop and its variations under varying conditions. This is an important factor in all theories of the electric arc and more accurate information on this point is certainly desirable.
6. Accurate determination of anode drop under varying conditions.
7. Study of small current arcs and particularly the glow to arc transition.
8. Mathematical study of some of the newer ideas on stability of discharges as developed by Barkhausen and others.
9. Cathode-ray study of stability of arcs such as used in electric welding. The spontaneous variations in current and voltage which are always taking place will probably be frequently beyond the capacity of the ordinary oscillograph. The influence of high frequency characteristics of the external circuit could be studied in this connection.
10. Stability of arc in magnetic field. Since arcs used in welding usually have quite strong magnetic fields, the influence of this factor in the stability of an arc is quite important.
11. Study of influence of nature of cathode surface on stability.
12. Study of influence of nature of anode surface on stability.
13. Study of passage of the deposited metal from the electrode to the work. Although a large part of the metal is deposited by liquid drops, it may be that a considerable portion passes in the form of vapor.
14. Study of the influence of superimposed alternating current of moderate and high frequency. The use of high frequency has been proposed for actual welding, but the influence upon the arc has not been studied in much detail.

It has also been suggested that the carbon welding arc be further studied, especially with respect to the blast of carbon vapor from the cathode spot.

University Activities

Through the initiative of the American Bureau of Welding, twelve engineering colleges and universities have become interested in various problems relating to welding. In addition to the research work conducted by professors, the students in several colleges write their theses on welding in preparation for the degree of B. S. or M. S.

It should be noted that welding, and especially electric welding, is receiving considerable attention in various universities abroad. Germany is probably leading in that respect because electric welding is considered to be of such importance that some colleges in that country confer the degree of Doctor of Engineering for any adequate research work on problems of welding.

In the Soviet Union, welding has received during the past year, an unprecedented expansion. To deal more adequately with the problem of a highly trained personnel, a special Welding Institute is being organized which will cost over $1,500,000, to train future welding engineers.

Electrical Machinery

ANNUAL REPORT OF COMMITTEE ON ELECTRICAL MACHINERY*

I. Organization and Activities

THE committee is organized with five permanent subcommittees, and its work has consisted of the review of papers, arrangement of programs for technical sessions, and the preparation of Standards and Test Codes.

Forty papers on electrical machinery were presented during the calendar year 1930. Others could have been made available if facilities for presentation and publication had permitted. The committee believes that the preparation of short and informal papers designed to bring out discussion at conventions should be encouraged, and that highly technical papers whose chief value is for reference should be presented before small groups in parallel sessions.

Standards

The Subcommittee on Transformers has been very active and during 1930 prepared "Recommendations for the Operation of Transformers" and brought to conclusion a revision of the A. I. E. E. Standards for Transformers.

The Subcommittee on Synchronous Machines, besides completing A. I. E. E. Standards for Capacitors, has initiated a number of revisions for the A. I. E. E. Standards for Synchronous Machines.

The Subcommittee on Mercury-Arc Rectifiers is working in close cooperation with the Sectional Committee on Rectifiers, which has under preparation Standards for Mercury-Arc Rectifiers.

Test Codes

Preliminary drafts of test codes for transformers, induction motors, direct-current machines and synchronous machines have been prepared. These codes are intended to provide definite instructions for the more generally applicable field and factory methods of conducting and reporting acceptance and other tests of general commercial value.

II. Resumé of Progress of the Art

SYNCHRONOUS MACHINES

Steam-Turbine Driven Alternators

The size of the single-shaft units has again been increased, two 200,000-kva., 0.8 power-factor, 1,800-r. p. m., single-shaft, tandem-compound, turbine-generator units (GE)† now being built for the Hudson Avenue Station of the Brooklyn Edison Company. They have double windings rated at 16.5 kv., and double-winding auto-transformers will step up the voltage to 27.6 kv.

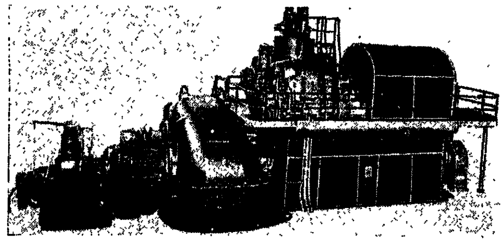

FIG. 1—50,000-KW., 3,600/1,800-R. P. M., VERTICAL-COMPOUND, TURBINE-GENERATOR UNIT (GE)—PACIFIC GAS & ELECTRIC CO.

A 110,000-kw., 1,200-lb., vertical-compound, double-winding turbine-generator unit (GE), with duplicate generators on the high- and low-pressure turbines, has been constructed for the Ford Motor Company.

A 50,000-kw., 3,600/1,800-r. p. m., 1,200-lb. unit, in which the high- and low-pressure elements were combined to form a vertical-compound turbine-generator set (GE) was constructed for the Pacific Gas & Electric Company and a duplicate unit is nearing completion. (Fig. 1.)

Three 18,750 kva., 3,600-r. p. m., turbine-generator units (W), the largest machines of this speed yet manufactured in this country, were put in operation at Baton Rouge by the Louisiana Steam Products Company. An outstanding feature of these machines is the internal propeller fan used, the success of which has created a new interest in internal fans for large machines.

High-voltage turbine generators rated 121,000 kva., 18 kv.; 147,000 kva., 22 kv.; and 94,000 kva., 22 kv. are now in the first stages of construction (AC).

The satisfactory completion of tests on a 9,375 kva.

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†Legend for Manufacturer Designation:

In order to conserve space and avoid numerous repetitions of the names of manufacturers, the following designation has been used throughout the report:

AC—Allis-Chalmers Manufacturing Co.
BB—American Brown Boveri Co.
CGE—Canadian General Electric Company
CW—Canadian Westinghouse Co., Ltd.
EM—Electric Machinery Mfg. Co.
GE—General Electric Co.
W—Westinghouse Electric & Mfg. Co.

*COMMITTEE ON ELECTRICAL MACHINERY:

P. L. Alger, Chairman,
L. F. Adams,
B. L. Barns,
W. M. Dann,
H. B. Dwight,
C. M. Gilt,
T. T. Hambleton,
A. L. Harding,
C.F. Harding,
S. L. Henderson,
L. F. Hickernell,
J. A. Johnson,
H. C. Louis,
A. M. MacCutcheon,
O. K. Marti,
V. M. Montsinger,
E. L. Moreland,
F. D. Newbury,
R. W. Owens,
E. B. Paxton,
A. M. Rossman,
R. B. Williamson,
H. L. Zabriskie.

hydrogen cooled, turbine generator (W) (Fig. 2) have encouraged the serious consideration of hydrogen cooled turbine generators for ratings above 30,000 kva.

Waterwheel-Driven Alternators

The year 1930 has been notable for the number of large hydro-electric developments which have either been contemplated or put into operation. Table I is a list of some of the more interesting hydraulic-driven generators installed or under construction during the past year.

The 77,500-kva. generators (GE) for the Dnieper River Development in Russia, operating under a hydraulic head of 123 feet are the largest waterwheel generators yet constructed. (Fig. 5.) The total weight of each generator will be approximately 880 tons, the weight of the rotor and shaft will approach 445 tons, and the shaft itself, which is 36 ft. long and 40 in. in diameter, with a 70-in. flange on each end, will weigh about 68 tons. The stator is fabricated in six sections with punchings and windings assembled in each section before shipment.

TABLE I—WATERWHEEL-DRIVEN ALTERNATORS

Purchaser—Location	No.	Kva.	R. p. m.	Type	Fig.	Mfr.
Amtorg Trading Co	4*	77,500	88.25	Vert	4	GE
Dnieper River (Russia)	1	77,500	88.25	Vert		GE
City of Seattle Skagit River	2	66,700	171.5	Umbrella		W
Inland Power & Light Co Ariel Development	1	56,250	120	Overhung		GE
Alcoa Power Co Chute-à-Caron	4	50,000	120	Vert		CW
New York Power & Light Corp Spier Falls	1*	47,000	81.8	Overhung		GE
Beauharnois Power & Light Co. St. Lawrence River	2	46,625	75	Umbrella		CGE
St. Lawrence River	2	43,883	75	Umbrella		CGE
Western Power Co. of Can. Ltd Ruskin Generating Station B. C.	1	44,000	120	Umbrella		CW
Lexington Water Power Co. Saluda Development	4*	40,625	138.5	Umbrella	3	W
New England Power Construction Co. Fifteen Mile Falls	4*	39,000	138.5	Umbrella		W
Shawinigan Engineering Co Rapid Blanc Development	4	36,000	109.1	Vert		CW
Pennsylvania Water & Power Co. Safe Harbor, Susquehanna River	4	31,111	109	Overhung		GE
	2	31,111	109	Umbrella		W
New Kanawha Power Co. New Kanawha River	4	30,000	150	Vert		W
Pacific Gas & Electric Co. Tiger Creek	2	30,000	225	Horiz		W
Gatineau Power Co Paugan Falls P. Q.	1	28,500	125	Vert		CW
James MacLaren Co Masson Power Development	4	28,000	166.7	Vert		CW
Shawinigan Water & Power Co Grand Mere, P. Q.	1	25,000	112.5	Vert		CW
Toccoa Electric Power Co. Blue Ridge	1	25,000	164	Umbrella		W
Montana Power Co. Morony	2*	25,000	81.8	Umbrella		W
Hydro Electrica Espanola Spain	2	25,000	375	Vert		GE
Union Electric Lt. & Pr. Co Osage River	6	23,888	112.5	Umbrella		W
Chats Falls Executive Board	8	23,500	125	Vert		CW
San Joaquin Light & Power Co. Merced Falls	1	4,000	128	Vert	4	W

*Included in report of last year.

The 31,111-kva., 109-r. p. m., umbrella-type generators (GE and W) for the Safe Harbor Development of the Pennsylvania Water & Power Company are to be driven by Kaplan-type turbines, and will operate as motors in a reversed direction to pump water back into the fore-bay for use during the peak-load periods.

High Frequency Generator

A 500-kva., 960-cycle generator (W) built for the American Brass Company will supply power for an electric furnace. The rotor required special construction to retain the field coils in place at the high peripheral speed of 20,000 ft. per minute.

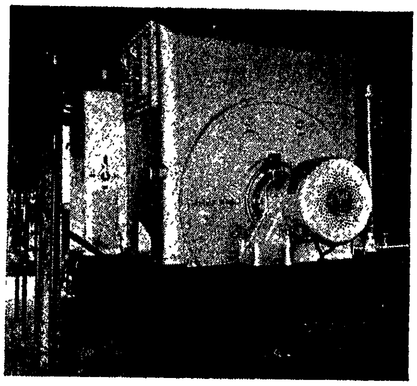

Fig. 2—9,375 Kva., Hydrogen-Cooled, Turbine-Generator (W)

A 666-kva., 960-cycle single-phase generator (GE) was placed in operation at Watertown (Mass.) Arsenal in November, 1930, and a 750-kva., 960-cycle, three-phase generator (GE) is being built for the American Brass Company.

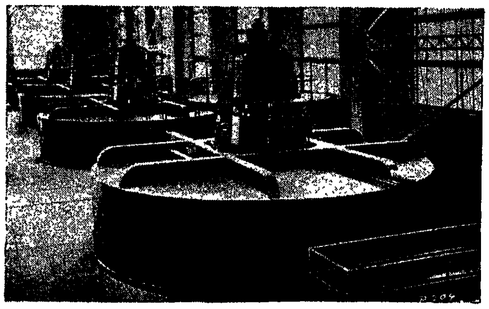

Fig. 3—Four 40,625-Kva., 138.5-R. P. M., Umbrella-Type, Waterwheel-Generator Units (W)—Saluda Development, Lexington Water Power Co.

Synchronous Condensers

A 50,000-kva., 13.2-kv., 600-r. p. m., 50-cycle hydrogen-cooled condenser (GE), equal in capacity to the largest air-cooled machines, has been constructed for the Southern California Edison Company. (Fig. 6.) The total capacity of hydrogen-cooled condensers now in service is 137,500 kva. with 70,000 kva. additional on order.

Two 15,000-kva., outdoor hydrogen-cooled condensers (W) have been constructed; one rated at 50 cycles, 750 r. p. m. for the Southern California Edison Company, and the other rated at 60 cycles, 720 r. p. m. for the Indiana & Michigan Electric Company.

A 7,500-kva., 6.6-kv., 900-r. p. m., 60-cycle air-cooled, outdoor condenser (AC) has been constructed for the Central Illinois Public Service Company. (Fig. 7.)

Industrial Synchronous Motors

The application of synchronous motors to industrial purposes is being extended as the knowledge of the starting, acceleration, and pull-in requirements is increased and as the prediction of these characteristics becomes more exact. A number of unique designs has been developed during the year.

A 500-hp., 72-r. p. m., vertical-shaft motor (GE) has been applied to a Fuller Lehigh coal pulverizer, in which the motor frame forms the base on which the pulverizer is built. The motor develops considerably more than normal torque from start to pull-in in order to obtain successful starting with a choked mill. Overvoltage for starting is supplied by a step-up auto-transformer.

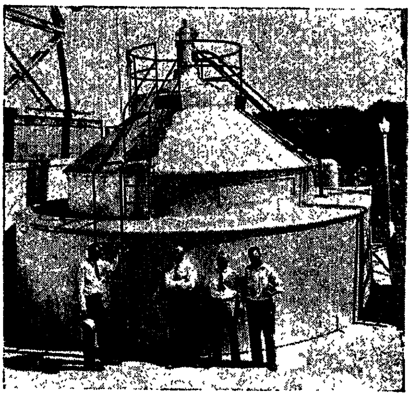

Fig. 4—4,000-Kva., 128-R. P. M., Vertical-Type, Outdoor, Waterwheel Generator (W)—Merced Falls, San Joaquin Light & Power Co.

A 700/350-hp., 2.3-kv., 277/138-r. p. m., three-phase, 60-cycle, two-speed synchronous motor (W) has been applied to a vertical centrifugal pump for the Ford Motor Company.

A new method for securing reduced starting kva. has been introduced, which utilizes the inherent reactance of the motor itself, a 3,000-hp. (GE), five 3,500-hp. (EM) and several smaller motors having been built. The stator is wound with two or more parallel circuits so arranged within the core as to obtain increased reactance when only one of the circuits is energized. The starting characteristics obtained are somewhat similar to those secured by using external reactors in series with the lines.

A 600-hp., 440-volt, 300-r. p. m., three-phase, 60-cycle, synchronous motor (EM) was applied for the first time for continuous reversing duty on a copper rolling mill, synchronous motors having been generally considered unsuitable for constant reversing duty on account of their inferior starting characteristics. The operating requirement that the mill be reversed from full speed forward to full speed reverse in five seconds necessitated special design of the stator and rotor to dissipate heating, which was accomplished by the use of ventilating spacers in the armature core and field poles and by special cage end-ring construction. (Fig. 8.) Three parallel circuits were used in the stator, which were switched successively both for forward and reverse acceleration in order to reduce the increment starting kva. demand.

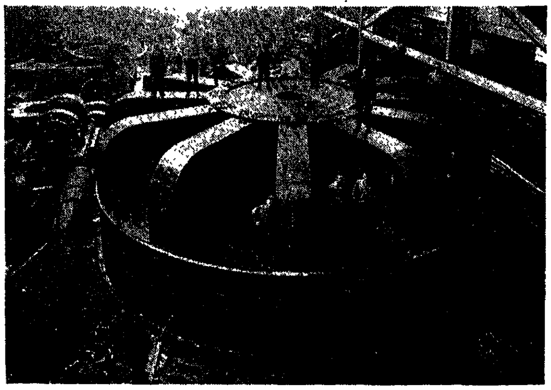

Fig. 5—77,500-Kva., 88.25-R.P.M., Vertical-Type, Water-wheel Generator (GE)—Dnieper River Development (Russia) Amtorg Trading Company

A slow-speed, vertical-shaft motor (EM) has been incorporated in a pulp hydrator base. The motor was provided with a thrust bearing which carries the weight of the rotor and hydrator rotating member. To permit adjustment of the clearance between the rotating and stationary members of the hydrator, the motor was provided with a micrometer raising and lowering device, the field poles being slightly longer than normal to permit a moderate movement of the rotor axially with respect to the stator.

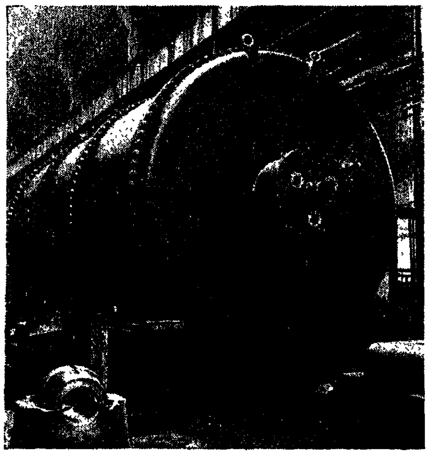

Fig. 6—50,000-Kva., 13.2-Kv., 600-R. P. M. 50-Cycle, Hydrogen-Cooled Synchronous Condenser (GE)—Southern California Edison Co.

Marine Synchronous Motors

Several electric-propelled vessels of interesting design were placed in service or are under consideration.

TABLE II—MARINE SYNCHRONOUS MOTORS

Vessel (or purchaser)	No.	Hp.	R. p. m.	Mfr.
S. S. Santa Clara	†2	6,300	120	GE
S. S. Morro Castle	†2	8,000	143	GE
S. S. Oriente	†2	8,000	143	GE
S. S. President Hoover*	†2	13,250	133	GE
S. S. President Coolidge	†2	13,250	133	W
United Mail S. S. Company (6 vessels)‡	12	5,500	125	GE

*Launched December 1930, Transoceanic service 1931.
†Included in report of last year.
‡Under construction.

The 13,250-hp., 133-r. p. m. ship-propulsion motors (GE, W) are the largest marine synchronous motors yet built. These motors are completely fabricated.

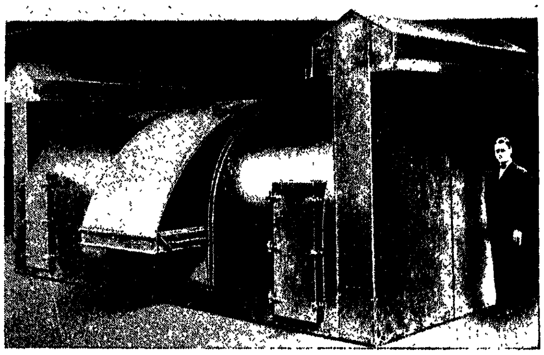

Fig. 7—7,500-Kva., 6.6-Kv., 900-R. P. M. 60-Cycle, Air-Cooled, Outdoor, Synchronous Condenser (AC)—Central Illinois Light Co.

Frequency Converters

There is a growing tendency to install large machines outdoors in order to reduce building costs. The first frequency-converter units to be so installed have been built during 1930 and will be placed in operation during 1931.

Two such units, the generators being rated at 21,000 kva., 0.7 power factor, 300 r. p. m., 25 cycle, one-phase, and the motors at 18,000 kva., 0.9 power factor, 300 r. p. m., 60 cycle, three-phase (W) will be installed at the Wayne Junction Substation of the Philadelphia Electric Company to supply power for the new Reading Railroad Electrification (Fig. 9). Conventional indoor design was followed, with spring mountings to absorb the single-phase torque pulsations, the machine being adapted for outdoor service by enclosing in a sectionalized sheet steel housing approximately 64 ft. long by 25 ft. wide.

INDUCTION MACHINES

A major activity of the manufacturers during the year has been the development of new lines of induction motors to conform with the frame sizes and mounting dimensions standardized by the National Electrical Manufacturers Association as announced in last year's report. In many cases this program has included a change in electrical design to improve the noise and torque characteristics. Much attention has also been given to the appearance in order to meet the ever more exacting aesthetic tastes of the public.

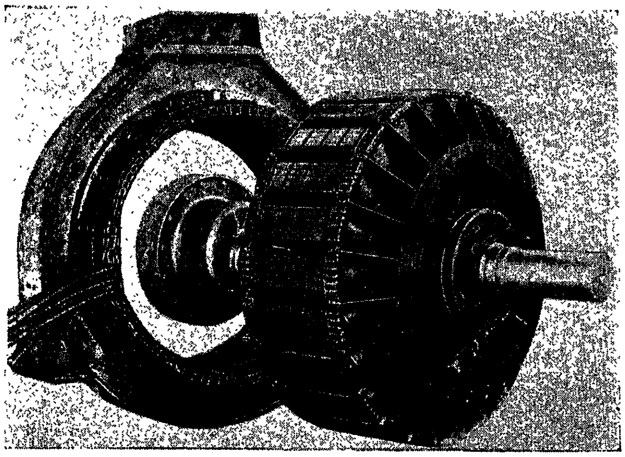

FIG. 8—600-HP., 440-VOLT, 300-R. P. M. 60-CYCLE, CONTINUOUS-REVERSING-DUTY, SYNCHRONOUS MOTOR (EM)—COPPER ROLLING MILL

Several manufacturers now furnish lines of motors in integral up to 100 hp. as well as fractional horsepower sizes for class I and class II hazardous locations (inflammable gases and combustible dust) as defined in the National Electrical Code.

Complete lines of totally-enclosed, fan-cooled continuous duty 55-deg. cent. motors as large as 250 hp., particularly suited for use in harmful dust conditions, have now been developed by many manufacturers and the use of this type is steadily growing.

An extensive application of a novel induction motor (GE) has been made to conveyor tables in steel mills. (Fig. 10.) The conveyor roller is a hollow cylinder mounted on ball or roller bearings rotating around a stationary supporting shaft on which the stator is mounted. The cylindrical convey roll, which surrounds the stator, serves as a secondary, the induced currents flowing in the solid steel inner surface of the roll.

D-C. MACHINES

Motors and Generators

An 8,000-hp., 800-volt, 40- to 100-r. p. m., motor, having a peak capacity of 22,000-hp., 2,900,000-lb. ft. torque, has been built (GE) for a blooming mill of the Illinois Steel Company. This is the largest single-armature motor employing fabricated construction for the major parts.

Two 5,000-hp., 40-r. p. m., double-armature motors were built (W) for operating the main rolls of the new 10,000-hp. blooming mills at the South Chicago Plant of the U. S. Steel Corporation, which is the most powerful mill yet built. Each of the two main rolls is driven by one of the motors, the two being kept at the same speed by electrical control instead of being geared together as in former installations. Each double motor has a peak-torque capacity of two million lb. ft. Power is supplied from three 3,000-kw. induction motor-generator sets. The series fields of the three generators are interconnected in such a way that parallel operation is secured with satisfactory division of load.

Planer motors up to 75 hp. rating with speed ranges by field control of 6 to 1 have been developed (GE and W), and further increases in size of this class of motor are under consideration.

A 50-hp., 1,600-r. p. m., 75-deg. cent. one-hour motor has been developed (W) for application on a coal cutter to meet a limiting over-all height of 12 in.

Six 3,500-hp., 330-r. p. m,, motors have been constructed (AC) for a 96-in. plate mill of the Illinois Steel Company. Power is supplied by two 6,000-kw. synchronous motor-generator sets.

Two motor-generator sets, consisting of two 3,000-kw., 600-volt, compensated generators driven by one 6,500-kva. synchronous motor, have been constructed (GE). These sets will deliver 6,000 kw. continuously with 9,000 kw. for two hours or 7,500 kw. continuously without overload.

Exciters

Further developments in "rapid response" exciters have occurred during the year, with the objects of securing higher efficiency and improved control. The use of a special Wheatstone Bridge type of rheostat (GE) enables the exciter to operate down to zero or even reversed voltage.

FIG. 9—21,000/(18,000)-KVA., 300-R. P. M. 25-(60)-CYCLE, ONE (THREE) PHASE, FREQUENCY-CONVERTER OUTDOOR HOUSING (W)—WAYNE JUNCTION SUBSTATION, PHILADELPHIA ELECTRIC CO.

A 90-kw., 3,600-r. p. m., direct-connected, turbine-generator exciter has been developed (W) which is one of the largest exciters ever built for this speed. (Fig. 11.)

Synchronous Converters

Four 5,440-kw., 167-r. p. m., 16,000-ampere, 25-cycle, synchronous converters were constructed (2 GE and 2 W) for a chemical plant in the Niagara Falls District. The converters are enclosed in volute housings, and the outgoing air is discharged outside the building. Direct-current voltage adjustment is obtained by means of tap-changing equipment on the supply transformers. A novel feature of construction used on two of these machines (GE) is a "tandem" commutator, which consists of two sets of shorter copper segments, together with insulation and clamping rings, mounted on a common support so arranged that air can pass between the adjacent ends of the two commutators where their segments are connected together. This construction (Fig. 12) results in lower temperature rise and smaller expansion strains and, consequently, a smoother running surface than is usually obtained with an equivalent single-unit commutator.

Transformers

Power Transformers

Extensive theoretical and experimental study of transient voltage phenomena was continued during the year, and the development of means for protection against lightning surges advanced rapidly. One indication of the progress made during the year is given by the successful outcome of full voltage flashover tests on a large transformer.

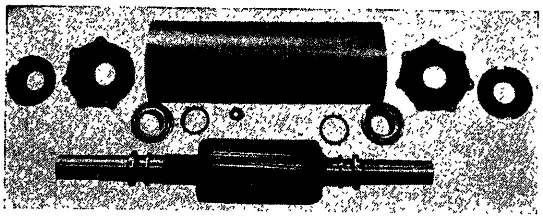

Fig. 10—40-Lb.-Ft., 250-Volt, 125-R. P.M., 25-Cycle, Conveyor-Roller Induction Motor (GE)

A 13,000-kva., 230-kv., wye-grounded, non-resonating transformer built for commercial use (GE) was subjected to a series of artificial lightning voltage tests. The transformer was connected to a lightning generator by a short transmission line insulated with fourteen 10-in. units, spaced 5¾ in. in suspension, which is used quite generally for 230-kv. service. The insulator strings were repeatedly flashed over without apparent damage to the transformer. The line insulation was then increased until the transformer bushings were flashed over. The transformer was subjected to repeated waves both above and below the bushing flash-over voltage, after which it withstood all A. I. E. E. standard tests.

A study of transient voltage phenomena within auto-transformer windings resulted in the development of the non-resonating auto-transformer (GE), of which several have now been built for 230-kv. service.

Through the development of the grounding neutral impedor (GE), the use of the non-resonating transformer was extended to include banks with neutrals isolated or grounded through resistance or reactance.

Investigation (W) has shown that a comparatively high resistance can be used in the neutral of a bank of power transformers and the bank will perform practically the same as though it were solidly grounded. The same result can be obtained with reactance in the neutral paralleled by a protective device, such as a lightning arrester. The internal voltages at points within the winding have been found to be practically identical for a bank with a solidly grounded neutral and for one with a reactance paralleled by a lightning arrester.

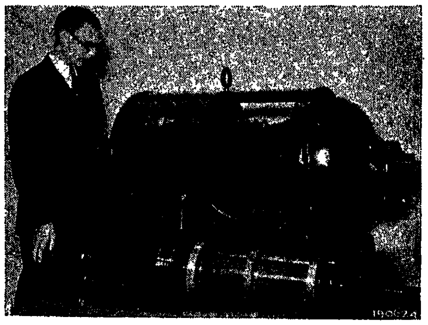

Fig. 11—90-Kw., 3,600 R.P.M., Direct-Connected, Turbine-Generator Exciter (W)

In order to extend the benefits of load-ratio control to small transformers, a lighter type of equipment has been developed for 15-kv. service (GE). This consists of a multi-point switch which permits the load current to leave each tap point over two paths; *i. e.*, over two switch arms which connect to the bridging reactor. A typical application of this equipment is represented by a 3,333-kva., 69.7/115 Y-13.8-kv., one-phase transformer, in which thirteen operating positions are provided by the installation of the control device in the low-voltage winding. In this type of construction all moving parts, that is, the ratio adjuster and two contactors, are mounted outside the main transformer tank.

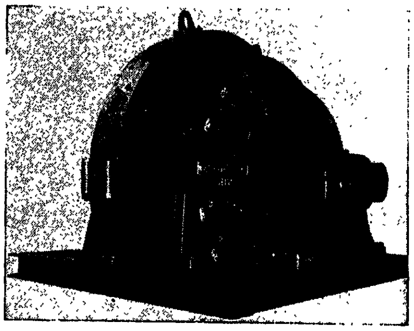

Fig. 12—5,440-Kw., 340/270-Volt, 16,000-Ampere, 25-Cycle, Shunt-Wound, Synchronous Converter with Tandem Commutator and Brushes (GE)

Several 5,000-kva., 13.2-kv., three-phase, furnace transformers, with a new type of tap-changing equipment, have been built (W) for the Ford Motor Company. These transformers deliver a normal low-voltage current of 12,800 amperes at 225 volts, with a maximum current of 19,200 amperes at 150 volts. A special motor-operated tap changer provides six different delta low voltages and a change from delta to star on the high-voltage winding gives six additional delta low voltages. Two individual tap changers are operated by one motor and all the voltages and connections are obtained by the operation of a single control switch at the switchboard.

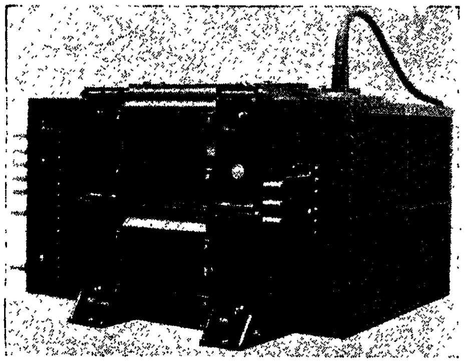

FIG. 13—4,200 KVA., 11,000,-915-46 VOLTS, 25-CYCLE, AIR-BLAST, LOCOMOTIVE TRANSFORMER (GE) (W)—PENNSYLVANIA R. R.

A 4,200-kva., 11,000-915-46-volt, air-blast transformer of special construction was built (coordinated design of GE and W) for installation in a locomotive where space is at a premium. (Fig. 13.) It was, accordingly, designed for minimum dimensions and weights, the floor space occupied being 6 ft. 8 in. by 7 ft. 3 in. and the total weight being approximately 26,000 lb. A 2,800-kva. transformer of the same type has also been developed. These transformers are suction air-cooled and of exceptional mechanical strength, being braced and insulated for the severe operating conditions incident to locomotive service.

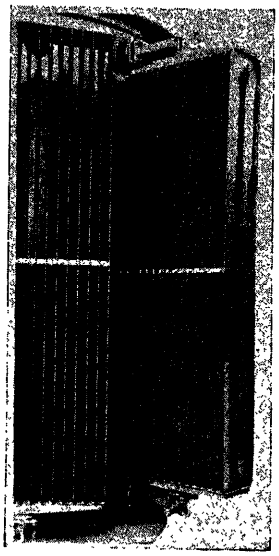

FIG. 14—OUTSIDE-EDGE-WELDED TRANSFORMER RADIATOR (W)

Power-Transformer Auxiliaries

While the method of cooling transformers by means of "banked" radiators was not used to any great extent following its development several years ago, it was extensively applied during the past year. About 200,000 kva. in transformers of this construction are in service and more than 600,000 kva. are now under construction (GE).

A new type of transformer radiator has been developed to replace the tubular type on all Westinghouse large self-cooled power transformers. (Fig. 14.) All of its joints are formed with edge welds on the outside of the radiator, and there are no crevices or flat surfaces where water can accumulate. The open construction facilitates cleaning and painting.

A 20,000-kva., 66-22-kv., load-ratio-control transformer, equipped with unusual pothead disconnecting switches has been built (W) for the State Line Generating Company. These high-voltage switches disconnect the transformer from the line and connect test bushings to the 66-kv. cable lines, which can then be tested with 330 kv., direct current. The pothead equipment also included oil reservoirs used to maintain pressure on the oil-filled cables to which the transformer is connected.

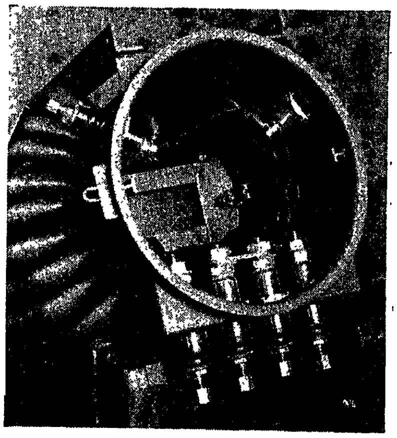

FIG. 15—100-KVA., 2,080-115/230-VOLT, 60-CYCLE, DISTRIBUTION TRANSFORMER EQUIPPED WITH DETACHABLE BUSHING (AC)—COMMONWEALTH EDISON CO.

A new no-load ratio adjuster has been developed (BB) which is operated through the side of the tank wall instead of the cover, making it more convenient to operate and permitting the tap position to be safely checked without deenergizing the transformer. A novel form of connection is used between the internal and external parts which permits engagement or disconnection of the two parts, when the transformer core is tanked or untanked, without the necessity of crawling inside to remove pins, bolts, etc.

Distribution Transformers

A new single-bushing, single-phase transformer has been designed (GE) for 110-kv. rural service. It is arranged for connection from line to neutral on a 110-

kv. circuit, which is insulated for 132-kv. service. In order to secure a low over-all height, the interior was so constructed as to give the equivalent of an inverted winding. The bushing was then connected to the bottom of the coil stack, thereby effecting a low height in spite of the large size of the bushing and the amount of insulation required for operation on a 132-kv. insulated line.

A detachable bushing has been developed (AC) for distribution transformers, particularly for installation where lightning conditions are abnormally severe, which can be replaced without removing the case from the pole. (Fig. 15.)

RECTIFIERS

The installation of rectifiers has continued to increase at a rapid rate, particularly when measured in terms of the aggregate kw. capacity.

	No.	Kw.
Put into operation during 1930	33	75,225
Put into operation during 1929	30	48,125
Increase	10%	58%
Put into operation during 1930	33	75,225
Being erected during 1930	26*	71,400*
On order at end of 1930	29	79,275
Total for 1930	88*	225,900*
In service at end of 1929	90	102,309
Grand total	178*	328,209*

*In addition one spare 500-kw. rectifier tank (without transformer) was supplied.

The mercury-arc rectifiers put into operation and being erected during 1930 and on order at the end of the year are shown in Table III.

The placing in operation of fourteen units with an aggregate rating of 40,000 kw. of 3,000-volt rectifiers

TABLE III—MERCURY-ARC RECTIFIER UNITS PUT INTO OPERATION DURING 1930 OR ON ORDER DECEMBER 31, 1930

Purchaser	No. of sets	D-c. volts	Kw. per set	Total kw.	Control	Service	Put in service	Manufacturer
American Gas & Electric, New York	2	610	500	1,000	Automatic	Railway	On order	Brown-Boveri
Boston Elevated Railway	2	600	3,000	6,000	Automatic remote control	Railway	Being erected	General Electric
Chile Exploration Co	1	650	1,000	1,000	Automatic	Heavy mine haulage	1930	General Electric
Clinton, Davenport & Muscatine Railway	1*	700	500	500*	Automatic	Railway	Being erected	Brown-Boveri
Commonwealth Edison Co	2	1,500	1,500	3,000	Manual	Railway	1930	Brown-Boveri
Commonwealth Edison Co	4	625	3,000	12,000	Manual	Railway	1930	Brown-Boveri
Commonwealth Edison Co	3	625	3,000	9,000	Manual	Railway	Being erected	Brown-Boveri
Commonwealth Edison Co	3	625	3,125	9,375	Manual	Railway	Being erected	General Electric
Consolidated Mining & Smelting Co. of Canada	2	650	6,500	13,000	Manual	Electrolytic	On order	Brown-Boveri
Consolidated Mining & Smelting Co. of Canada	1	650	6,500	6,500	Manual	Electrolytic	On order	General Electric
Delaware, Lackawanna & Western R. R. Co.	12	3,000	3,000	36,000	Manual	R. R. electrif'n	1930	General Electric
Delaware, Lackawanna & Western R. R. Co.	2	3,000	2,000	4,000	Automatic remote control	R. R. electrif'n	1930	General Electric
Detroit, City of	1	600	2,000	2,000	Automatic	Railway	On order	General Electric
Edmonton, City of	1	575	1,325	1,325	Manual	Railway	1930	Brown-Boveri
Hershey Chocolate Company	1	600	500	500	Manual	Interurban-railway	1930	General Electric
I. G. Farbenindustrie for Standard Oil Co. of Louisiana	1	3,500/9,600	2,200	2,200	Manual	Electro-chemical	Being erected	Brown-Boveri
Iowa Nebraska Light & Power Co	1	600	1,000	1,000	Manual	Railway	1930	Brown-Boveri
Italian State Railways	2	2,900	2,000	4,000	Automatic	R. R. electrif'n	1930	General Electric
Long Island Railway Co	5	650	3,000	15,000	Automatic	Railway	Being erected	Brown-Boveri
Los Angeles Railway Corp	2	600	1,500	3,000	Automatic remote control	Railway	On order	General Electric
Montreal Tramways Co	2	600	1,500	3,000	Automatic remote control	Railway	Being erected	General Electric
Montreal Tramways Co	2	600	1,500	3,000	Automatic remote control	Railway	1930	General Electric
New York Board of Transportation	10	625	3,000	30,000	Automatic remote control	Subway	Being erected	General Electric
New York Board of Transportation	13	625	3,000	39,000	Automatic remote control	Subway	On order	General Electric
Northern Indiana Public Service Co	1	1,500	3,000	3,000	Automatic	Railway	Being erected	Brown-Boveri
Paris Orleans Railway, France	1	1,500	1,500	1,500	Automatic	R. R. electrif'n	On order	General Electric
Philadelphia, City of	2	630	2,500	5,000	Manual	Subway	1930	Brown-Boveri
Public Service Co. of No. Ill., Chicago	1	600	1,900	1,900	Manual	Railway	1930	Brown-Boveri
Public Service Co. of No. Ill., Chicago	1	600	1,900	1,900	Automatic	Railway	1930	Brown-Boveri
Quebec Power Co	1	550	1,200	1,200	Automatic	Railway	Being erected	Brown-Boveri
Regina, City of	1	575	1,200	1,200	Manual	Railway	On order	Brown-Boveri
Saskatoon, City of	1	575	600	600	Automatic	Railway	1930	Brown-Boveri
Trenton Transit Co	3	600	1,400	4,200	Manual	Railway	On order	Brown-Boveri
Totals:								
Put in service	33			75,225				
Being installed	26*			71,400*				
On order	29			79,275				
Grand total for year	88*			225,900*				

*In addition one spare 500-kw. rectifier tank (without transformer) was supplied.

on the Delaware, Lackawanna & Western Railroad Electrification (Fig. 16) was the outstanding event of this year. This is the first installation of 3,000-volt rectifiers in the United States and the first use anywhere of so great a capacity of such units. It is also the first instance of a major railroad electrification relying entirely on rectifiers for the supply of power. These rectifiers are equipped with excited grids and with automatic compounding.

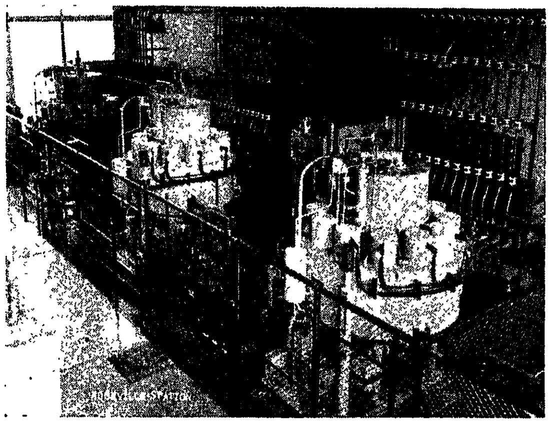

Fig. 16—3,000-Kw., 3,000-Volt, Mercury Arc Rectifiers (GE)—Roseville Substation, Delaware, Lackawanna & Western R. R. Electrification

Another outstanding feature is the very large number of units ranging in voltage from 550 to 650 volts with a current rating in excess of 3,000 amperes, notable among which are 23 sets (GE) with an aggregate capacity of 69,000 kw. on order by the New York Board of Transportation. (The first seven units of this order were reported last year under the heading "City Subways of New York.")

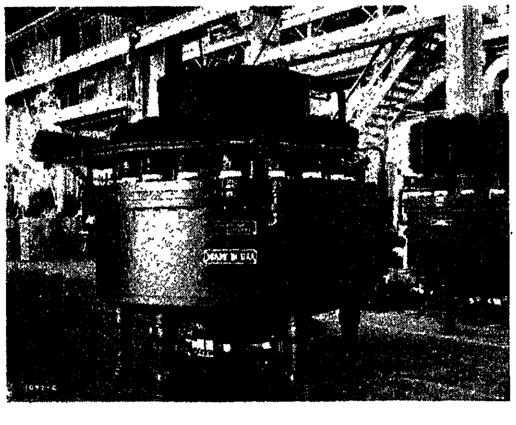

Fig. 17—3,000-Kw., 650-Volts, Mercury Arc Rectifier (BB)—Long Island R. R.

Five units (BB), having a normal rating of 4,650 amperes at 650 volts, with overload ratings up to 15,000 amperes for twenty seconds, are being erected for the Long Island Railroad (Fig. 17). These rectifiers have eighteen anodes and normally operate from a 25-cycle source of supply but are arranged for immediate throw-over to a 60-cycle source of supply in the event of failure. The transformers are also suitable for operation at either 11 or 33 kv.

A 2,200-kw., high-voltage electric furnace set is also being erected (BB). The d-c. voltage may be varied from 3,500 to 9,600 volts by means of load-ratio control on the rectifier transformer. This is the highest voltage for commercial rectifiers which has been reported in this country. Smaller units of higher voltage have, however, been used for large radio broadcasting stations in Europe.

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Electrochemistry and Electrometallurgy

ANNUAL REPORT OF COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY[*]

THIS report covers the period 1929 and 1930, inasmuch as no report was made in 1929.

It is believed worthwhile to indicate the magnitude of the electrochemical and electrometallurgical industries in terms of installed capacity and yearly power consumption. The figures for the United States are as follows:

Approximate installed operating capacity, kw	7,000,000
Approximate percentage of National total generating capacity	18
Approximate annual power consumption, kw-years	4,900,000
Approximate percentage of total	36
Number of workers	1,000,000
Value of product	$12,000,000,000

Quantities and percentages such as these would seem to warrant the liveliest interest on the part of men having electrical engineering training, particularly the younger men who find themselves faced with limited opportunities for advancement in those more standardized fields of the electrical art involving the design and manufacture of apparatus for the production and distribution of electrical energy. The development of new materials or processes based upon the utilization of this power is a field requiring talent of high order and one which it seems should be very attractive to men of electrical training who can and will superpose on an electrical background a knowledge of the fundamentals of physical chemistry.

Below is given a list of the more important industries whose basic processes are dependent upon the utilization of electricity for other than mechanical purposes:

Production of Metals by Wet Electrolysis. Copper, Nickel, Sodium, Zinc.

Production of Metals from Fused Electrolytes. Aluminum, Barium, Beryllium, Calcium, Magnesium.

Non-Metallic Electrolytic Products. Caustic, Chlorine, Hydrogen, Oxygen.

Electrothermic Products. Abrasives, Carbides, Carbon, Ferro-Alloys, Graphite, Refractories.

Miscellaneous. Cleaning and Surface Treatment of Metals, Dry Cells, Electric Steel Melting, Electrolytic Synthesis Organic Compounds, Electroplating, Electrostatic Precipitation, Inductive Melting and Heating, Nitrogen Fixation, Pasteurization and Sterilization, Secondary Batteries, Water Purification, Welding.

When the process problems of these industries are analyzed it will be found that they should be attacked by men who have been trained to deal with intangibles, and that most of the phenomena may be resolved into elements among which an electrical engineer who has been soundly trained in the basic science of his art should feel at home. Pursuit of these problems will probably lead him far from consideration of the newest thing in circle diagrams or the latest refinement in slot design but he will have broader scope for his imagination and the mental technique bred by electrical training.

The foregoing comments have been made because there are many who feel that the electrical industry is more in need of increased outlet for power than of further small gains in the efficiency of electrical apparatus *per se,* and that the great body of expectant young electrical engineers must look for adequate opportunities for advancement more to the fields of utilization and electrical processes than to the conventional ones of apparatus and generation.

Below is given an outline of the more important developments in electrochemical and electrometallurgical art that have become known during the past two years.

Copper

Although copper refining is probably the largest of the electrochemical industries in point of tonnage, no important modifications of electrochemical process have been reported although operating economies have been improved by advances in mechanical equipment and materials handling facilities.

Sodium

Metallic sodium is now being produced on such a large scale and so cheaply by electrolytic methods that it is the cheapest pure metal in terms of cost per unit volume. Its electrical conductivity is high enough so that its cost on a conductivity basis is lower than that of any other metal. These facts have led to a proposal that electrical conductors be formed of metallic sodium enclosed in a thin-walled tube of some non-magnetic alloy steel.

Metallic sodium is finding increasing application in connection with certain synthetic organic reactions whose nature is not disclosed and certain electrochemical interests are said to be preparing to manufacture sodium on an unprecedented scale.

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[*] COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY:

P. H. Brace, Chairman,
Lawrence Addicks,
T. C. Atchison,
Farley G. Clark,
S. K. Colby,
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N. R. Stansel,
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J. L. Woodbridge,
C. D. Woodward.

Zinc

The success of electrolytic zinc refining plants was noted in the 1928 report of this committee. This development has since been subject to severe competition because of improvements in thermochemical methods. Electrothermal methods have also received the attention of investigators and it is probable that another year will see marked changes in zinc technology due directly to the application of electricity in one way or another.

Aluminum

The Hoopes process of producing very pure aluminum has become of increasing commercial importance, particularly for containers for various articles in the drug and pharmaceutical field. Although the electrical conductivity is appreciably higher than that of ordinary commercial aluminum it has not been commercially applied as electrical conductor material. Accurate alloy investigations have been made possible by this very pure material and the knowledge thus gained has assisted materially in the development of the strong aluminum alloys.

The usual Hall process rarely produces aluminum purer than 99.7 per cent, while the Hoopes process is regularly producing metal better than 99.98 per cent pure and some metal has been produced by this process having a purity of 99.99 per cent. The process is carried out in a three-layer cell, wherein the metal to be purified exists as a molten anode alloy and rests on the bottom of the cell. The electrolyte consists of a mixture of cryolite, aluminum fluoride and barium fluoride. The purified aluminum is electrolytically deposited in a layer of pure molten aluminum floating on top of the electrolyte. Graphite electrodes are employed to lead the current out of the aluminum layer. The cell operates at a voltage varying from 5 to 7 volts and normally a current of 20,000 amperes is employed.

By anodic treatment in wet electrolytic cells aluminum may be given a tough, adherent and corrosion resistant surface of oxide which serves as a base for color and which is also finding use for protection of aluminum alloy aircraft structure from severe corrosion attack such as that of salt spray and sea-water. This development is still going forward rapidly and is expected to become of much greater importance in aluminum technology.

Electro-plating with aluminum on copper and other base metals has been accomplished by the use of a fused electrolyte of low melting point comprising the chlorides of aluminum and sodium. Tough, adherent, and non-porous deposits of pure aluminum are produced and many commercial uses will no doubt be found as the technique is improved.

Barium

Barium is one of the alkaline-earth elements and is characterized by great reactivity and interesting thermionic properties. It is produced by the electrolysis of fused barium salts and has been receiving considerable attention because certain of its alloys have useful thermionic properties. It has found commercial application in a nickel-base alloy for spark plug electrodes and has been of interest as an essential constituent of alloys intended for use as cathodes in thermionic devices. Such barium alloys are, in general, electric furnace products.

Beryllium

During the past few years the metal beryllium has received a great deal of attention, which has been primarily due to the results of systematic research both in this country and abroad. Beryllium may be produced by an electrolytic process which consists of the electrolysis of mixed beryllium oxyfluoride and barium fluoride. The only commercial ore of beryllium is a silicate of beryllium and aluminum. The beryllium oxide content of available ores lies between 6 and 12 per cent. The production of beryllium has been carried out both in this country and abroad.

The future of beryllium does not appear to lie in its use as a basic material, but rather as a minor constituent in more or less complex alloys.

About the only use thus far developed for the pure metal is as windows in X-ray tubes, inasmuch as beryllium is extremely transparent to X-rays. Experimental use in pistons and piston rings has been reported. Continued research will doubtlessly develop new uses for this interesting metal, inasmuch as it possesses a combination of high elastic modulus, low expansivity and lightness which is very attractive to many who are interested in mechanical developments. Its electrical resistivity is approximately 6.7 microhms per cu. cm. at room temperature.

Magnesium

This metal is produced by the electrolysis of molten magnesium chloride and more recently by means of processes in which magnesium oxide is dissolved in a bath of fused fluorides and decomposed by electrolysis to give the metal. The production of magnesium in the United States has increased from approximately 50,000 lb. in 1921 to more than 1,000,000 lb. in 1930. During 1930 magnesium forgings have appeared on the American market and with continued research it is expected that increased quantities of strong magnesium alloys in the form of castings and forgings will be rather extensively employed particularly in aircraft. With improved production technique purer metal is being produced and the susceptibility to corrosion lessened in consequence.

The outstanding difficulty in the way of increasing the use of magnesium has been the development of suitable alloys and fabricating processes and great strides are being made in this direction.

Electrotechnology of Gases

The treatment of gaseous mixtures by electrical discharges in order to effect chemical reactions that would not ordinarily occur has received a great deal of attention. The work of Fischer and Peters in Germany is particularly interesting in that they find it possible to produce acetylene from methane with an energy consumption that compares favorably with that required by the conventional calcium carbide process. The cracking of heavy hydrocarbon vapors by corona discharge also shows some possibilities. A great deal of research is going on in connection with the chlorination of hydrocarbons such as methane, pentane, etc., and this promises a considerable expansion in the use of chlorine, which is an electrolytic product. Research investigations of the chemical effects of bombardment by high-speed electrons should also be mentioned.

Abrasives—Carborundum

Tungsten carbide cutting tools have found increasing application and this has necessitated the development of improved abrasive wheels for shaping them. As a consequence special grades of carborundum are being made, apparently of unusual purity, from which grinding wheels specially adapted to the shaping of carbide tools are made. Carborundum base resistors for high temperature electric heating furnaces have been considerably improved, and several manufacturers have designed about this type of resistor commercial furnaces for operating temperatures between 1,000 deg. and 1,400 deg. cent.

Aluminum silicate refractories of very high melting point are being fused in electric furnaces and cast into blocks and shapes for various purposes, particularly for parts for glass-melting furnaces. The melting and casting of such highly refractory substances is a new and interesting departure in industrial ceramic technology.

Cleaning of Metals

A wet electrolytic process for the removal of scale from metals which is said to be competitive with pickling and free from many of its objections has been put on a commercial basis. Hydrogen embrittlement is prevented by the automatic deposition of a thin film of lead on any area of clean metal as soon as it is exposed by scale removal. This lead film may be allowed to remain as a protection against corrosion or removed by anodic oxidation by reversal of the electrolyzing current.

Electrochemical Standards

The interest in our electrochemical standards for the international ampere and the international volt has been continued and during the coming summer cooperative measurements on these standards will be carried out at the Physikalisch-Technische Reichsanstalt. For this purpose Dr. G. W. Vinal, Chief, Section of Electrochemistry, U. S. Bureau of Standards and a member of this Committee is being sent to Germany. He will also make measurements at the Laboratoire Central d'Electricite in Paris, and the National Physical Laboratory in England.

Primary and Secondary Batteries

During the past year the American standard for dry cells has been revised and a new standard approved by the American Standards Association. This standard has been published by the Association and also by the Bureau of Standards as Circular No. 390. The technical requirements of the Government specifications are identical with those of the American standard, but the Government specification is being revised to accord with the form prescribed by the Federal Specifications Board for all Government specifications.

The Federal specifications for automotive storage batteries have been approved and published during the year. These are designated as W-B-131 and are contained in section 4, part 5 of the Federal Standard Stock Catalog.

The past twelve months have witnessed a considerable decline in the demand for primary battery products in general due to the business depression and the reduction in the number of battery operated radio sets in active use. This has naturally affected most the production of B batteries, though the production of 6-in. dry cells, many of which were also used for radio, has been seriously affected as well. The demand for flashlight batteries seems actually to be on the increase due perhaps to the appearance on the market of a rather wide variety and a considerable number of inexpensive flashlight cases which have apparently been widely bought.

The general decrease in demand for battery products has resulted in a tendency to reduce prices and on the part of at least the larger manufacturers to strengthen quality. Many of the smaller manufacturers have been forced out of the business as a natural consequence.

The year has brought the development of the industrial flashlight battery intended for use by public service corporations, railroads, theaters, and manufacturing organizations where the demand on the battery is considerably heavier than in ordinary flashlight use. At a recent conference at the Bureau of Standards two tests were standardized as representative of the industrial types of service and this has greatly facilitated and intelligently guided the development of satisfactory cells for this specific application.

Special radio B batteries of superior performance have been developed in response to demand created by radio-equipped automobiles for police squad use as well as for privately owned machines.

In the 6-in. dry cell group there has been a further advance in the life of the better telephone cells. Certain makes have reached the remarkably high figure of 360 days on the standard light intermittent test which compares with a maximum of about 180 days ten years ago.

An interesting new development which has occurred in the primary battery field during the past year is the introduction by one manufacturer of an air depolarized portable caustic soda battery designed primarily for use as an A battery for specially designed radio receivers using the new two-volt tubes and operated entirely by batteries. It is hoped that radio receivers of this type will develop wide application in rural districts where power is not available for operating electric radio sets and where storage batteries cannot be conveniently charged. This so-called air cell radio A battery is said to be good for a year's average service with one of these receivers. The basis of its operation is the absorption by a porous carbon electrode of the oxygen from the air which is carried to the surface of the electrolyte where it acts as a depolarizer for the cell. While the principle employed is not a new one, its application to a portable practical battery is believed to be new.

During the year, the revised American Standard for Dry Cells has been published, both by the American Standards Association of 29 West 39th Street, New York City, and by the Bureau of Standards in its Circular No. 390.

In the field of storage batteries the recent publication of the Federal Specification for Automotive Batteries, designated as W-B-131, may be mentioned.

A new storage battery, the Drumm alkaline cell, which involves the use of an electrolyte of potassium hydroxide with electrodes of nickel and other substances not disclosed, is said to provide reduced weight, increased efficiency, and the possibility of recharging in a 30 minute period. The e. m. f. is 1.5 volts. Successful trials in heavy trucking service are reported from England.

Electric Melting Furnaces

The demand for better metallurgical performance of arc furnaces is bringing about refinements in control gear among which are the use of tap-changing transformers to enable more precise voltage control and a tendency toward the adoption of hydraulic drive for electrodes, in which pilot valves responsive to furnace current, voltage or kva. operate to control fluid flow to the electrode driving cylinders. More prompt response, improved sensitivity and absence of hunting are said to be provided by hydraulic operation.

Induction furnaces of the submerged ring type are finding somewhat wider application owing to improvements in refractories and in a few places abroad have been used on high-nickel alloys and for superheating cast iron for high-strength castings.

Coreless induction furnaces operating at high frequency have found commercial application in sizes up to two tons, with power ratings up to 600 kw. High-frequency generating units of 1,250 kw. are being built to supply 3½ ton furnaces. A common frequency is 980 cycles, but the trend is downward, particularly for large units. Commercial frequencies have been successfully applied and one manufacturer has successfully operated experimental four-ton units at 60 cycles, the entire kva. requirement being supplied by a motor-generator set. Considerable attention has been given to the technique of refining in these induction furnaces and some success has been attained.

Oxygen-free copper from large inductively heated furnaces is a commercial possibility of the near future. Such a material would avoid some of the weaknesses of present commercial copper and in particular its tendency to embrittlement when subject to hot reducing gases. Unusually high ductility may make it interesting for some mechanical uses.

The heat treating of steel and other alloys in controlled atmospheres by means of electric resistor furnaces has become a well established and rapidly growing practise. Initially forced by severe requirements of steel users it appears that economies may be realized which will offer further incentives to advance in this direction. Such processes are being applied to copper, brass, low-carbon and high-carbon steels, nickel, corrosion-resistant alloys, and magnetic materials over a range of temperatures extending from 500 deg. cent. to 1,200 deg. cent.

Water Purification

Electrolytic purification of water has been receiving considerable attention following the announcement, in Germany, of a process and apparatus in which water is passed through a succession of diaphram type electrolytic cells which cause concentration of ionogens in the electrode compartments. It is susceptible of large-scale operation but so far has been used mainly to complete the purification of distilled water.

Sterilization of Milk

The electropure process of milk conditioning effects pasteurization by passing the raw milk rapidly between carbon electrodes where it is heated by the passage of 60-cycle current. This scheme enables refinements in the control of the time and temperature variables that have hitherto been impracticable and the quality and uniformity of the product are thereby enhanced.

Electrostatic Precipitation

The results of test of improved hot-cathode vacuum rectifiers indicate that it will be possible to improve the operation and decrease the physical dimensions of the electrical end of precipitation plant. Increased use of powdered coal firing has caused the ash which is carried up the stack to be troublesome and electrostatic precipitator equipment is finding application in this connection. The same fundamental ideas are being applied to the separation of suspended solids from liquids. The purification of insulating oils is a case in point and it is stated that by electrostatic cleaning higher breakdown values can be obtained than by methods now in general use.

Metal Powders

Finely divided metals find numerous uses in chemical technology and as pigment in the decorative arts. Electrolytic means have been developed for producing copper, tin, nickel, silver, and lead in crystalline form in sizes as fine as 500 mesh.

MISCELLANEOUS PROCESS AND PLANT

Mercury Arc Rectifiers

There are under construction for a Canadian Plant mercury arc rectifiers rated at 6,500 kw. each (10,000 amperes, 650 volts) to be used for the electrolytic production of hydrogen.

Rotary Converters

Another electro-chemical plant has installed synchronous converters with load ratio control type transformers to furnish direct current for an electrolytic process. These machines are rated at 5,440 kw. each (16,000 amperes, 340/370 volts). These machines are also of interest because of their use of volute housings as part of the ventilation system.

Electrodeposition of Tungsten

The electrodeposition of tungsten in the wet way from alkaline baths has been accomplished on a laboratory scale. Tungsten possesses such marked resistance to acid attack and to wear that this development may prove to be of considerable industrial importance.

Heat Treating Furnaces

A marked interest was shown by the steel industry in the use of electric furnaces for heat treatment service. One plant installed two 1,100-kw. resistor type furnaces 50 tons capacity each, one 1,000-kw. similar furnace; and other furnaces, making a total of 4,500 kw.

The use of artificial atmospheres in electric furnaces for heat treatment processes is making considerable progress. One steel plant has installed 2,000 kw. in furnace capacity for bright annealing of steel strip.

Electrically heated and controlled apparatus for controlling the composition of the gases used are coming into evidence.

The special requirements of the nitriding process which involves heating to approximately 550 deg. cent. articles of special alloy steel (containing small amounts of Cr, Al, Mo, and Ni) in an atmosphere of ammonia has led to the development of furnaces with special provisions for circulating the ammonia. Heat transfer is effected by forced convection instead of by radiation. It appears possible that the application of this principle will find extended application in special-purpose furnaces in which control of atmosphere is important.

In both the heat-treating and melting fields the refinements of metallurgical technique and the growing recognition of the value of high quality and uniformity of product have brought about such profound changes in the design and operation of furnaces that they are coming to resemble machine tools rather than the piles of brick that the word usually calls to mind.

CONCLUSIONS

It is believed that this report reflects the more important trends in electrical process technology and hoped that it may draw the attention of electrically trained men to the very interesting possibilities in the field of the development of processes and materials dependent upon the forces that only electricity can bring into play.

The Chairman wishes to acknowledge the assistance given by members of the Committee and by numerous individuals in the preparation of this report which is respectfully submitted on behalf of the Committee on Electrochemistry and Electrometallurgy.

Discussion

Lawrence Addicks: There is no need to confine the list of metals produced (by electrochemical means) to copper, nickel, sodium and zinc. Most of the silver and gold and a large minority of the lead is so produced.

An important new use of calcium is well under way, namely its use to displace bismuth from lead. Much work is being done on a cheap method of producing the lead-calcium alloy used as a reagent and one of the most promising starts with calcium carbide, an electrochemical product. One of the more expensive methods was by way of Frary metal, another electrochemical product.

Electrochemistry is about one-third each, chemistry, physics, and electrical engineering. Very few are proficient in all three.

J. Lester Woodbridge: I have been able to obtain considerably more detailed information in regard to the Drum alkaline storage battery than is contained in this report. It appears that the positive plate used in the tests in electric traction service conducted under the supervision of the Irish Free State last summer was of the standard nickel oxide type. The negative plate consisted of the standard nickel plated negative grid used in the nickel alkaline battery into which metallic zinc was plated from the electrolyte which consisted of a solution of potassium hydroxide and a soluble compound of zinc.

I have this information on quite reliable authority and believe it to be correct.

Magnus Unger: Mention should be made of the development of fused quartz mirrors for observatories, work being done by the Thompson Research Laboratory of the General Electric Company.

Electrophysics

ANNUAL REPORT OF THE COMMITTEE ON ELECTROPHYSICS*

THE annual report of the Committee on Electrophysics has generally taken the form of an account of the progress in the field of electrophysics during the preceding year. In view of the steady increase of the activity in this field the matter to be covered has increased greatly, and the report for the year 1929-1930 was a lengthy one in spite of all efforts to keep its size down to a minimum.

At a meeting of the committee held January 30, 1931 its field of activity and in particular its annual report were discussed at considerable length. It was the sense of the committee that it was one of the most important of its functions to bring to the attention of electrical engineers the progress being made in electrophysics. It was felt very strongly, however, that this cannot be done in the best possible fashion by reporting the progress for a year at one time and publishing it as a unit. Accordingly, the committee decided that it could be of much greater service to the engineering profession if its reviews of the progress in electrophysics were published from time to time by subjects instead of annually as a unit. As a result the plan was adopted of publishing reviews of the progress of electrophysics by subjects in ELECTRICAL ENGINEERING. Each contribution will aim to cover the progress in its particular field from the date of the preceding report as nearly up to the date of publication as is possible. A tentative schedule of the proposed subjects is as follows:

Magnetism and Magnetic Materials.
Propagation of Electric Waves.
Electric Discharges in Gases.
Dielectrics.
Thermionics and Photoelectricity.
Vacuum Gas Discharge and Photoelectric Tubes.
Electric Conduction in Solids.
Electromagnetic Theory.

In addition the Committee plans to sponsor from time to time for publication in ELECTRICAL ENGINEERING papers by recognized authorities on various subjects in electrophysics of interest to electrical engineers. One such paper is published herewith. After all the reviews for any one year have been published, they may be collected and published together in the TRANSACTIONS if it should be considered desirable.

Magnetism and Magnetic Materials

The following review of progress in magnetism and magnetic materials covers the period since the last report of the Electrophysics Committee. The progress in other phases of electrophysics will be covered similarly in succeeding reviews. The Committee also may offer from time to time papers on subjects in electrophysics of interest to electrical engineers.

MAGNETISM

Our understanding of ferromagnetism has advanced during the period since our last report (JL. A. I. E. E. **49**, 721, 1930) in several important respects. Heisenberg's interaction theory, which refers the stability of magnetization to the low potential energy of codirected electron spins in neighboring atoms, has been applied by Powell (*Proc. Phys. Soc.* **42**, 390, 1930) to explain the change in dimensions which take place when iron and nickel lose their ferromagnetism on heating. This change, a decrease in the case of iron, an increase in the case of nickel, is isotropic, being thus wholly unlike the principal part of magnetostriction which differs greatly in different crystallographic directions. It is concluded from the fact that both signs of change occur that some account must be taken, at least in the case of iron and probably in all cases, of atoms more remote than the immediate neighbors. Becker and Kirsten (*Zeitsch. f. Physik* **64**, 660, 1930) who identify the stabilizing forces with internal elastic strains, have succeeded in getting rather good agreement between the permeability of highly stressed nickel as measured and as calculated from limiting magnetostriction and the elastic moduli. Rankin (*J. Roy. Tech. Coll.* Glasgow **2**, 385, 1931) has continued his experiments on magnetostriction in overstrained metals. Akulov has continued his discussions of the relations between magnetostriction, magneto-resistance and elasticity concluding in his latest papers (*Zeitsch. f. Physik* **67**, 794, 1931; *Phys. Zeits.* **32**, 107, 1931) that the magnetic behavior of single crystals is fully explained by a dual process of reversals and rotations of the magnetic elements and that the magnetic properties of polycrystalline metal *without large scale anisotropy* can be calculated from data obtained for monocrystals. McKeehan (*Rev. Mod. Phys.* **2**, 477, 1930; **3**, 190, 1931) has reviewed the content and relations between the current theories of ferromagnetism and some of the recent experimental evidence pertinent thereto.

Several papers, in addition to that of Powell, already referred to, deal with the experimental and theoretical

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*COMMITTEE ON ELECTROPHYSICS:
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V. Bush,
W. G. Cady,
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C. L. Fortescue,
W. S. Gorton,
W. B. Kouwenhoven,
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K. B. McEachron,
L. W. McKeehan,
H. Nyquist,
Leigh Page,
W. S. Rodman,
J. Slepian,
W. F. G. Swann.

aspects of the Curie point. Tyler (*Phil. Mag.* [7] **11**, 596, 1931) shows that the decrease of apparent saturation values with rise of temperature is practically according to the same law for iron, cobalt, and nickel, and that this is consistent with the idea that in all three metals single spinning electrons are free to change their axial direction, although in all these cases the average number of such magnetizable electrons per atom is greater than one. According to these data, therefore the ferromagnetic unit is sub-atomic rather than atomic. Above the Curie point it appears (Stoner, *Phil. Mag.* [7] **10**, 27, 1930) that atoms begin to act as units. Forrer and Hoffmann (*Comptes Rendus* **191**, 1046, 1930) present new evidence for a doubling of the (ferromagnetic) Curie point in nickel, the coercive force first decreasing, then increasing, and finally decreasing again as the temperature rises. An apparent disagreement between two experimenters, Weiss and Bates, in regard to the temperature at which the specific heat anomaly becomes greatest as the Curie point is approached has been dissolved by new evidence. Bates (*Proc. Phys. Soc.* **42**, 441, 1930; **43**, 87, 1931) now also finds this temperature to be where $- d\,I^2/d\,T$ is maximum; his earlier experiments were vitiated by an irreversible change in the properties of his material (manganese arsenide) produced by the small rise in temperature (magneto-caloric effect) associated with applying the magnetizing field. Incidentally, the specific heat anomaly is here far too large to be ascribed to an elementary magnet like that in iron or nickel.

The anomalous temperature coefficient of electrical resistance for ferromagnetics near their Curie points is closely associated with their magnetizability. Gerlach (*Zeitsch. f. Physik* **59**, 847, 1930; *Ann. der Physik* [5] **6**, 772, 1930) and Borelius (*Ann. der Physik* [5] **8**, 261, 1931) present opposing opinions regarding the anomaly. The former in agreement with earlier work of Cabrera regards the high-temperature state (above the Curie point) as normal and the low-temperature state as possessing an abnormally low resistance, the latter supports the contrary view that it is the low-temperature or completely magnetized state which has normal resistance. The transition as the Curie Point is approached from below is the same whichever view is taken.

The closely related subject of heat production during magnetization and demagnetization has been examined in a preliminary way by Gilbert (*Comptes Rendus* **191**, 1309, 1930) who finds no cooling in cobalt steel at H up to 18,000 except that attributable to the magneto-caloric effect of Weiss. The more complete report of Ellwood's results (*Phys. Rev.* [2] **36**, 1066, 1930) confirms his earlier finding of a cooling in carbon steel at low values of H on the ascending branch of a loop, and announces a second stage of cooling at moderate values of H. It should be noted that the magneto-caloric effect would account only for a minute heating in this part of the loop.

An effort has been made by Bitter (*Phys. Rev.* [2] **37**, 91, 1931) to coordinate ferromagnetic behavior with the small scale imperfection of metallic crystals recently predicted by Zwicky (*Helvetica Physica Acta* **3**, 269, 466, 1930; **4**, 49, 1931). Frenkel and Dorfman (*Nature* **126**, 274, 1930) deal with the same problem on purely thermodynamic principles, deciding that a large crystal cannot act as a magnetic unit.

Experiments on the Barkhausen effect in a rotating magnetic field (Cisman, *Ann. der Physik* [5] **6**, 825, 1930), make it more plausible than ever to suppose that the occurrence of a discontinuity in magnetization requires a definite degree of divergence between the applied field and the local magnetization. There is, in fact, a decided parallelism between Cisman's Barkhausen effects and hysteresis in rotating fields, most recently studied by Seiyama (*Mem. Kyushu Univ. Coll. Engg.* **5**, 227, 1930). Heaps and Bryan (*Phys. Rev.* [2] **36**, 326, 1930) have shown that large changes in magnetization and in magnetostriction are simultaneous. Bozorth has just discovered (*Nature* **127**, xxx, 1931) that in a very slowly changing magnetic field the Barkhausen discontinuities which can be detected by a high-speed oscillograph occur in closely grouped sets with quiet intervals between them. These compound events, in proximate analysis, can easily be mistaken for single events. This apparently explains the wide disagreement between published statements as to the volume of metal affected in a single discontinuity. The time required for the spreading of a major magnetic disturbance has been studied by Sixtus and Tonks (*Phys. Rev.* [2] **36**, 1441, 1930).

The gyromagnetic effect, hitherto only observed in ferromagnetic materials—most recently by Barnett (*Phys. Rev.* [2] **36**, 789, 1930)—has now been measured for a paramagnetic material by Sucksmith (*Proc. Roy. Soc.* [*A*] **128**, 276, 1930; *Proc. Phys. Soc.* **42**, 385, 1930). The phenomenon is merely easier to observe in ferromagnetics on account of their easier magnetization.

In studies on diamagnetic and weakly paramagnetic metals the theory has been improved by Landau (*Zeitsch. f. Physik* **64**, 629, 1930) and Teller (*Zeitsch. f. Physik* **67**, 311, 1931) so that better predictions are now possible as to the diamagnetism to be expected from conduction electrons. On the experimental side relatively enormous changes in susceptibility—much larger than the changes in conductivity make probable—have been reported by Honda and Shimizu (*Nature* **126**, 990, 1927) and by Bitter (*Phys. Rev.* [2] **36**, 978, 1930), both of whom measured the susceptibility of copper as affected by cold work and annealing. Banta (*Phys. Rev.* [2] **37**, 634, 1931) has attempted without success to duplicate Bitter's findings.

Spectroscopic evidence that some atomic nuclei have a small magnetic moment continues to accumulate (Fermi, *Zeitsch. f. Physik* **60**, 320, 1930; Goudsmit and Young, *Phys. Rev.* [2] **35**, 1418, 1930; Frisch and Ferchmin, *Naturwiss*, **18**, 866, 1930). The effect upon gross magnetic properties of such nuclear magnetic moments as have yet been shown to exist must be very small.

Effects of magnetic fields on electrical resistance and electric potential with or without the presence of thermal currents and temperature differences have been reviewed on the basis of the new electron theory of metals by Sommerfeld and Frank (*Rev. Mod. Phys.* **3**, 1, 1931). The proper mode of description of these galvanoelectric, thermoelectric, galvanomagnetic and thermomagnetic effects have been discussed by Perrier (*Helvetica Physica Acta* **3**, 317, 400, 1930). The conditions are especially complicated in the case of ferromagnetics. Pugh (*Phys. Rev.* [2] **36**, 1503, 1930) has shown for iron that the magnetization, I, or the ferromagnetic induction, B-H, is more important than either H or B in fixing the magnitude of the Hall e. m. f. Stierstadt (*Zeitsch. f. Physik* **65**, 575, 1930; **67**, 725, 1931) has studied magneto-resistance in electrolytic iron for both longitudinal and transverse magnetizations. Williams and Sanderson (*Phys. Rev.* [2] **37**, 309, 1931) present new data on magneto-resistance in nickel strips of different mechanical history.

The magneto-resistance of bismuth single crystals at extremely low temperatures, below 20 deg. K, has been studied in detail by Schubnikow and de Haas (*Nature* **126**, 500, 1930; *Proc. Amsterdam Acad.* **33**, 363, 418, 1930), who find a whole series of unexpected phenomena. Unlike the magneto-resistance at higher temperatures the relative change in resistance is no longer a smoothly varying function of the applied field, H, nor of the azimuth in any crystallographic plane yet examined. At higher temperatures, however, theory has caught up with experiment, for Frank (*Zeitsch. f. Physik* **64**, 650, 1930) has shown that the straightening out of $\Delta R/R$ *vs.* H curves at high H values, first observed by Kapitza, is completely accounted for by the quantum theory of electronic conduction. The parabolic increase of $\Delta R/R$, formerly supposed to be called for by the theory, is only possible for relatively limited ranges in H.

One of the most puzzling experimental results recently published is that of Allison and Murphy (*Am. Chem. Soc. Jl.*, **52**, 3796, 1930), who report that the magnetic double refraction (Faraday Effect) in certain solutions is characteristic, not only of the elements present but even of the number of isotopes of each, and furnishes a highly sensitive means for chemical analysis.

In the domain of magnetometry Sanford has been investigating magnetic permeameters, particularly those for use at high inductions (*Bu. Std. J. Res.* **4**, 177, 703, 1930; **6**, 355, 1931). A new level of precision in magnetic curve tracing has been attained by Haworth (*Bell System Tech. Jl.* **10**, 20, 1931; *Rev. Scient. Instr.* [N. S.] **2**, 125, 1931) who compensates the torque of a fluxmeter suspension by a photoelectric current depending upon the momentary deflection. Brüche (*Zeitsch. f. tech. Physik* **12**, 94, 1931) has considerably refined the methods for exploring magnetic fields by narrow beams of cathode rays. Freed and Kasper (*Phys. Rev.* [2] **36**, 1002, 1930) have improved the accuracy of Gouy's method for measuring the susceptibility of weakly magnetic solutions.

A stimulating book by S. R. Williams[1] gives a readable account of the experimental side of the subject of magnetism, with especial emphasis on ferromagnetism.

An important announcement regarding magnetic units as adopted by the International Electrotechnical Commission was made by Dr. Kennelly at the Winter Convention in New York. The electrophysics committee is by no means unanimously in accord with the suggestions of the international body. Some of our members feel that the already existing confusion in regard to the physical significance of B and H is increased rather than diminished by giving physical dimensions to their ratio. It is interesting to notice that a body of German engineers went even farther than the I. E. C. in the effort to rationalize empirical relations (*Elektrotech. u. Maschinenbau* **48**, 950, 1930).

MAGNETIC MATERIALS

The results of many investigations carried out in the past three or four years confirm the view that crystal grain size is one of the important factors in magnetic materials. Yensen (*Metals and Alloys*, **1**, 493-495; 1930) has proposed an expression for the hysteresis loss in iron in terms of the crystal grain size and impurities in the metal, leading to the conclusion that for perfect single crystals, free from impurities and internal strain, the hysteresis loss vanishes. Gerlach has more recently arrived at a similar conclusion. (*Zeitsch. f. Physik*, **64**, 502-506; 1930). On the other hand Von Auwers and Sizoo (*Zeitsch. f. Physik*, **60**, 576-580; 1930) conclude that crystal grain size has much less influence on remanence than on hysteresis loss and coercive force.

What promises to be of great importance is the announcement by Cioffi (*Nature*, **126**, 200-201; 1930) that ordinary polycrystalline iron may be made to acquire very high permeability by heat treating at high temperature in hydrogen. The reported initial and maximum permeabilities are 6,000 and 130,000, respectively, and the coercive force and hysteresis loss are respectively 0.05 gauss and 300 ergs/cu. cm./cycle, for $B_m = 14{,}000$. Later unpublished values give 180,000 for the maximum permeability, 0.025 gauss for the coercive force and 190 ergs/cu. cm./cycle for the hysteresis loss for the same maximum induction. These properties are ascribed partly to purification of the iron and partly to the hydrogen actually absorbed in the metal. Further correlation appears to be necessary between crystal grain size and magnetic properties in view of these results, since the grain size of this material appears to be of little importance.

The existence of the A_3 point in carefully purified iron occurring reversibly between 907 deg. cent. and

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[1] "Magnetic Phenomena," McGraw-Hill, 1931.

910 deg. cent. has been confirmed by Roberts and Davey (*Metals and Alloys* **1**, 648-654; 1930), by X-ray crystallographic determinations. This fact has recently been a matter of some dispute (Yensen, A. I. M. & M. E., *Inst. Metals Div.*, 320-332; disc. 332-349; 1929).

The increasing importance of nitrided steels has led to further investigations of the iron-nitrogen system. Qualitative and quantitative measurements by Lehrer (*Zeitschr. f. Electrochem.*, **36**, 460-473; 1930) by means of magnetization-temperature curves have been used to construct the equilibrium diagram for the iron-nitrogen system. The results show that up to 11 per cent nitrogen there are four phases, in agreement with the X-ray determinations of Hägg (*Zeitsch. f. Physik. Chem.* **8**, 455-474; 1930) and Eisenhut and Kaupp (*Zeitschr. f. Electrochem.* **36**, 392-404; 1930). Köster (*Archiv. f. Eisenhüttenwesen* **3**, 637-648; 1930) has shown that nitrogen in α-iron remains in supersaturated solution even after slow cooling, requiring prolonged heating at low temperatures for complete separation, with a resultant increase in conductivity and increase in coercive force from 4 to 7 gauss. The segregation of nitrogen in the supersaturated solution is further accelerated by cold working (*Archiv f. Eisenhüttenwesen*, **3**, 649-658; 1930).

A number of alloys of iron and non-magnetic elements has been investigated. Pure electrolytic iron having a trace of phosphorus has been found to have better magnetic properties than commercial silicon steel. (*Gayler, Metallwirtschaft*, **9**, 677-679; 1930.) The iron-silicon system has been studied by Haughton and Becker, (*Iron and Steel Inst. Jl.*, **121**, 315-335; 1930) using metals of higher purity than heretofore. The existence of phases corresponding to the compounds FeSi, and Fe_3Si_2 have been confirmed, and in addition a phase which is probably the compound Fe_2Si_5. The addition of 14.5 per cent silicon lowers the Curie point of iron to 490 deg. cent. A magnetic transformation point occurring at 82 deg. cent. in the Fe_3Si_2 phase confirms the earlier work of Murakami (*Tohoku Imp. Univ. Sci. Rep.*, **10**, 79-92, 1921). Oya (*Tohoku Imp. Univ. Sci. Rep.* **19**, 235-245; 1930) has found that additions of vanadium to iron first raise the Curie point then depress it, so that it is room temperature for 35 per cent vanadium. The alloys of iron and chromium with approximately 18 per cent chromium have been found to have zero magnetostriction (Dean, *Rensselaer Polytech. Inst. Bull. No. 26*, Eng. and Sci. Series; 1930). Fischer (*Rensselaer Polytech. Inst. Bull. No. 28*, Eng. & Sci. Series; 1930) has found that this range of alloys has higher permeability and is less sensitive to quenching strains than other alloys of this group. This behavior has already been observed in permalloy (Buckley and McKeehan, **26**, 261-273; 1925) and is in accordance with McKeehan's theory of magnetostriction (*Phys. Rev.* **28**, 158-166; 1926). Kussmann, Scharnow, and Messkin (*Stahl u. Eisen*, **50**, 1194-1197; 1930) have found that additions of copper up to 0.7 per cent increase the resistance of iron to corrosion without impairing its magnetic and electrical properties. A general deterioration of these properties is obtained for higher copper concentrations.

The relation of magnetic properties to mechanical hardness has been investigated by Messkin (*Stahl u. Eisen*, **50**, 105-106; 1930) who has found that cold rolling increases the remanence and coercive force of carbon steel; and by Herbert (*Proc. Roy. Soc.*, **130**, 514-523; 1930) who has observed age hardening of steel and non-magnetic metals subjected to a changing magnetic field.

Sachse and Hasse have found that (*Zeitsch. f. Physik Chem.*, [A] **148**, 401-412; 1930) regular crystals of ferromagnetic ferric oxide, Fe_2O_3, are unstable at all temperatures, the susceptibility falling by 60 per cent in 4 years at room temperature. The fact that ferric oxide has 10^{-10} the conductivity of the ferromagnetic metals, leads Sachse (*Zeitsch. f. Phys. Chem.*, [B] **9**, 83-91; 1930) to conclude that free electrons cannot be concerned in its magnetic properties. The ferrites of magnesium, lead, copper, and nickel are also ferromagnetic at ordinary temperatures, cadmium ferrite being sometimes ferromagnetic and sometimes paramagnetic (Holgersson and Serres, *Comptes Rendus*, **191**, 35-37; 1930). In mixtures of Fe_2O_3, NiO, and C_0O, Veil (*Comptes Rendus*, **190**, 181-183; 1930) has found a higher coefficient of magnetization for the composition represented by $(Fe_2O_3)_2$ $NiOC_0O$.

A somewhat higher Curie point has been obtained for nickel by Jordan and Swanger (*Bur. Std. Jl. of Res.* **5**, 1291-1307; 1930) which is believed to be due to the greater purity of their nickel specimen. Sadron has found that (*Comptes Rendus*, **190**, 1339-1340; 1930) small additions of chromium to nickel, causes the saturation value at absolute zero to diminish linearly with chromium content, the Curie point for an alloy with 12 per cent Cr being absolute zero.

Widespread interest in the nickel-iron alloys coming under the collective name of permalloy is indicated by its numerous modifications to meet specific needs. Elmen has obtained very high initial permeability and resistivity in nickel-iron alloys by additions of molybdenum, chromium or tungsten (U. S. Pat. 1,757,178; *Jl. Frank. Inst.* **207**, 583-618; 1929). Stäblein (U. S. Pat. 1,760,326) has obtained high resistivity by additions of silicon. Bandur (U. S. Pat. 1,743,089) and Yensen (*Elec. Jl.* **27**, 214-218; 1930) report that with suitable heat treatment some nickel-iron alloys may be made to acquire sensibly constant permeability over a limited range of induction. Similarly, Smith and Garnett (U. S. Pat. 1,746,500) have obtained substantially constant permeability in nickel-iron alloys by additions of copper. Also, Gumlich, Steinhaus, Kussmann and Scharnow (*E. N. T.*, **7**, 231-235; 1930) report that high resistivity and small variation of permeability with magnetizing force are obtained in nickel-iron alloys by small additions of manganese.

Von Auwers, (*Wiss. Veroffentlich Siemens-Konzern* **9**, 262-293; 1930) has studied the effect of strain on the magnetic properties of permalloy. The results of numerous experiments indicate that the properties of permalloy cannot be accounted for on the basis of strain alone.

Methods of design and testing of permanent magnets have kept abreast with the improvements in magnetic properties. Elenbaas (*Physica*, **10**, 273-286; 1930) has derived a formula for calculating the field intensity in a toroid with an air-gap, based on the assumption that the demagnetization curve is an ellipse; this should prove useful in the design of permanent magnets. It is well known that the magnetization of a ferromagnetic material by a steady field is considerably increased by the superposition of an alternating field. Schrankow and Janowsky (*Zeitsch. f. tech. Physik* **11**, 429-432, 1930) apply this method of bringing permanent magnets to high inductions. An accurate method of testing bent permanent magnets has been described by Webb and Ford (*I. E. E. Jl.*, **68**, 773-778; 1930) whereby both B and H are measured by means of search coils and a ballistic galvanometer. The superior properties of cobalt-steel as permanent magnets have found application in the magnetic compass for aircraft, disturbances from stray magnetic fields being avoided by shielding with hipernik, a nickel-iron alloy of high permeability (J. R. Gier, *Elec. Jl.*, **27**, 114-115; 1930).

The need for accurate and constant substandards of frequency has stimulated further work on vacuum tube oscillators controlled by the resonant magnetostrictive vibrations of magnetic materials. This method of control requires the use of materials which have good magnetostrictive properties and small temperature coefficients of permeability and expansion. Vincent (*Proc. Phys. Soc.* **43**, 157-165; 1931) has extended the range of the magnetostriction oscillator of Pierce, (*Proc. Am. Acad. Sci.*, **63**, 1-47; 1928) to radio frequencies by using corronil, a nickel-copper-manganese alloy, and glowray, a nickel-iron-chromium alloy (*Proc. Phys. Soc.* **41**, 476-486; 1929); the latter, particularly, has a high degree of stability. Smith (*Proc. Phys. Soc.* **42**, 181-189; 1930) has determined the nature and magnitude of the coupling between the mechanical vibrator and the electric circuit for a toroidal specimen of a nickel-iron alloy vibrating radially in its fundamental mode. Muzzey (*Phys. Rev.* **36**, 935-947; 1930) has used the magnetostriction oscillator as a means of exciting cylinders of stainless steel in studying the dependency of frequency of vibration on length and diameter of the cylinders.

ACKNOWLEDGMENT

The Committee is indebted to Professor L. W. McKeehan, of its membership, and to Mr. P. P. Cioffi for material for this report.

General Power Applications

ANNUAL REPORT OF COMMITTEE ON GENERAL POWER APPLICATIONS[*]

THE principal activity of the Committee during the past year has been in arranging and carrying out of plans for the Industrial Session held at the Winter Convention. As this Committee is interested in the application of electricity to all industries which are not specifically covered by other committees of the Institute, it was agreed that papers to be of interest to the greatest number of engineers should be of a general nature and not confined to a specific industry or application. The papers presented were consequently arranged and prepared with this thought in mind. During this period of industrial depression an increasing amount of attention is being given to the subject of reducing manufacturing costs and it was hoped that industrial engineers would find in these papers various ideas which could be applied to their own problems.

INDUSTRIAL PAPERS PRESENTED

Besides those papers presented at the Winter Convention several other papers of an industrial nature were presented at district meetings. Following is a list of those papers which have come to our attention:

Philadelphia Meeting Oct. 13 to 15, 1930:

Air Conditioning in Industry, by A. H. Clogston of the Cooling and Air Conditioning Corp.

A New System of Speed Control—A-C. Motor-Driven Power Station Auxiliaries, by A. M. Rossman of Sargent and Lundy, Inc.

Louisville Meeting, Nov. 19 to 22, 1930:

Electricity in the Cement Industry, by R. H. Rogers of the General Electric Company.

Electric Power in the Lumber Industry, by A. H. Onstad of Weyerhaeuser Timber Co.

Winter Convention, January 26 to 30, 1931:

Electron Tubes in Industry, by W. R. King of General Electric Co.

Automatic Regulators in Industry, by J. H. Ashbaugh, Westinghouse Electric and Manufacturing Co.

Electrical Distribution Systems for Industrial Plants, by W. J. McClain, of Louis T. Klauder Co.

The Synchronous Motor with Phase-Connected Damper Winding as a Drive for High-Torque Loads, by M. A. Hyde, Jr., Westinghouse Electric and Manufacturing Co.

The Design and Application of Synchronous Motors to Meet Special Requirements, by D. W. McLenegan and A. G. Ferriss of General Electric Co.

Pittsburgh Meeting, March 11 to 13, 1931:

Conversion and Distribution of General Purpose D-C. Power in Large Industrial Plants, by R. D. Abbiss, Carnegie Steel Co. and D. C. West, Westinghouse Electric and Manufacturing Co.

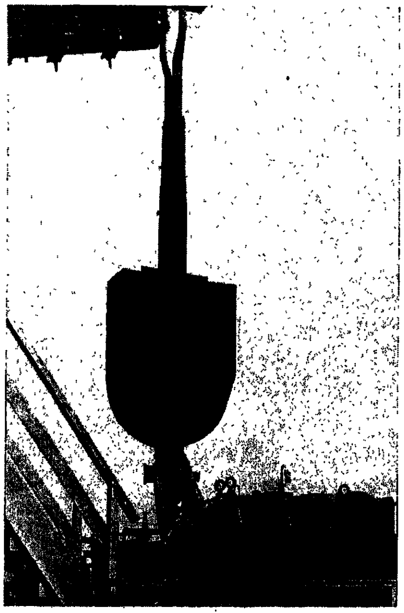

FIG. 1—COMBINATION PUMPING UNIT FOR OIL WELLS INCLUDING MOTOR, GEARS, AND CONTROL

Symposium on *Interconnection Between Utilities and Industries*. Several papers.

The Use of Electricity in Large Annealing Furnaces, by J. C. Woodson, Westinghouse Electric and Manufacturing Co.

A Modern Electrified Dairy Plant, by A. J. Dreux, Reick-McJunkin Dairy Co. and H. C. Brunner, Westinghouse Electric and Manufacturing Co.

REVIEW OF INDUSTRIAL PROGRESS

Since the past year has not been one of great industrial development or activity, it is felt that this report should include not only a review of the major industrial developments but also should indicate the trend of development along both application and apparatus lines in industry.

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[*] COMMITTEE ON GENERAL POWER APPLICATIONS:

C. W. Drake, Chairman,
E. A. Armstrong,
James Clark, Jr.,
J. F. Gaskill,
Clyde D. Gray,
John Grotzinger,
Fraser Jeffrey,
A. M. MacCutcheon,
H. A. Maxfield,
John Morse,
N. L. Mortensen,
A. M. Perry,
D. M. Petty,
F. O. Prior,
H. W. Rogers,
L. D. Rowell,
M. R. Woodward.

PETROLEUM INDUSTRY

During the past year pipe-line transportation of liquid fuel over long distances has been extended to include gasoline. Electric pumping stations supplied with central station service, are increasing in number and proving their economy. The latest development is an electric station with three 800-hp. pumping units which is completely controlled from a dispatching office about 15 miles away. This is the Sand Springs Station of the Texas Empire Pipe Line that connects Oklahoma oil fields with the Chicago refineries. The supervisory control permits the dispatcher to exercise complete control over the station and gives a visual indication of its operation. The dispatcher can tell at a glance what units are operating, what the intake and discharge pressures are and as much other pertinent information as could be obtained if the operator were in the station. In case of trouble the equipment is shut down automatically and the dispatcher advised of the nature of the trouble.

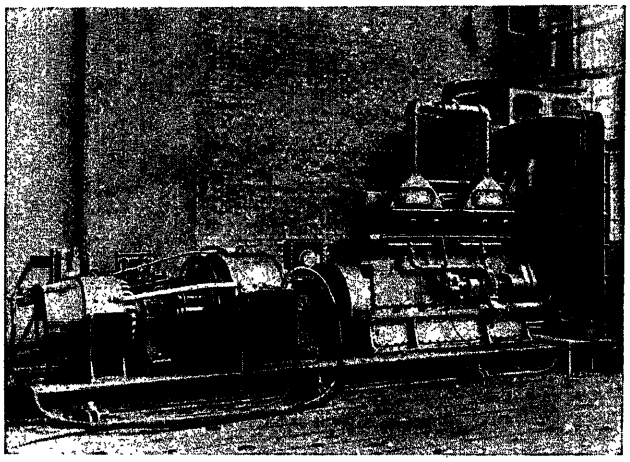

FIG. 2—PORTABLE DIESEL ENGINE-DRIVEN SET FOR VARIABLE VOLTAGE OIL WELL DRILLING OUTFITS (SHOP VIEW)

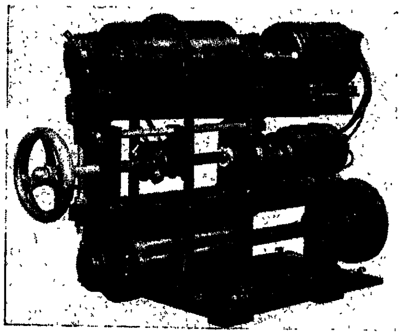

FIG. 3—SELSYN GENERATOR AND CONE PULLEYS FOR SECTIONAL PAPER MACHINE DRIVE

Development in electrical oil field pumping and drilling equipment has been towards the use of combination, or factory assembled apparatus which eliminates many parts and reduces the installation expense in the field. One of the latest pumping units consists of a combination of gear, motor, and control built in one unit. The equipment is weatherproof and requires no housing. The unit is also provided with change gears for obtaining several speeds as required for various pumping conditions.

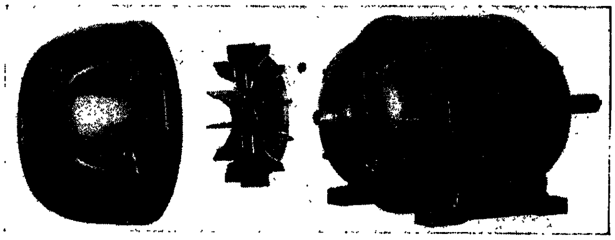

FIG. 4—TOTALLY ENCLOSED FAN-COOLED MOTOR WITH FAN AND FAN CASING REMOVED

During the past year several variable voltage d-c. oil well rotary drilling outfits have been built and put in service, using Diesel engines as prime movers. These outfits are being used primarily on locations where central station power is not available. The ease and simplicity of control obtainable with the variable voltage d-c. system, its low energy requirement and flexible operating characteristics, make this system very desirable for this type of oil service.

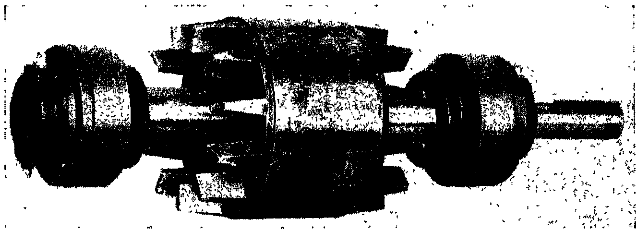

FIG. 5—INDUCTION MOTOR ROTOR SHOWING CARTRIDGE TYPE BALL-BEARING HOUSINGS

Two installations are also reported where standard a-c. drilling equipments were installed and supplied with power from Diesel engine-driven generators, and, although this system may lack some of the desirable features of the variable voltage system, it makes it possible to use standard a-c. motors for pumping and other uses.

PULP AND PAPER INDUSTRY

Sectional paper machine drives were installed during the year on a wide variety of machines from low-speed cylinder to high-speed fourdrinier and the use of section regulators of the carbon pile type instead of the contact making type was quite noticeable. A description of some of these carbon pile regulators is given in Mr. Ashbaugh's paper, presented at the Winter Convention.

A regulator for sectional drives using Selsyn equipment so that the main regulating equipment may be mounted remote from the paper machine has been placed in operation during the year. At the paper machine, in connection with each sectional motor, is a Selsyn generator driven through suitable cone pulleys which provide necessary speed adjustment or "draw" between the various sections. The resistance elements of the regulator are of the carbon pile type.

Rural Electrification

The use of electricity on the farm has increased rapidly during the past year and reports from central stations indicate that approximately 90,000 farms were connected to their lines during the year. This represents an increase of 16 per cent over the total number previously connected. This growth is accounted for partly by the interest of the power companies in the farm load and partly by improved rate structures and power schedules. But of fully as great importance however is the increasing list of electrical equipment which is available and specially adapted for farm service. The attention being given to the production of milk with a low bacteria count has done much to force the installation of dairy sterilizing and dairy refrigerating equipment and these devices in connection with other dairy and household equipment make a very desirable electrical load.

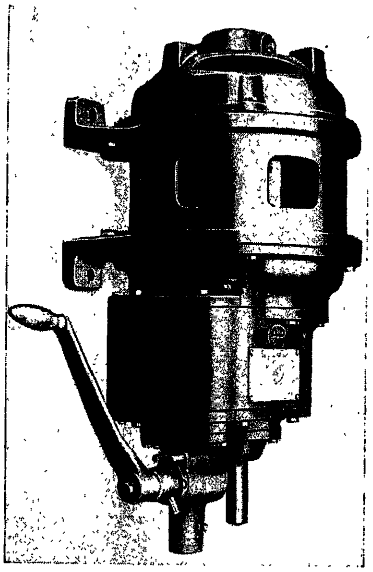

Fig. 6—Motor with Built-In Four-Speed Transmission Showing Speed Changing Lever

Engineering research and investigation have proven the possibility of using 5-hp. electric motors for practically all stationary work such as silo filling, feed grinding, wood sawing, etc., instead of using 15- or 20-hp. tractors. Numerous improvements have recently been made in the design and construction of portable motor equipment for such service which includes automatic linestarters with thermal overload protection, effective methods of belt tightening, and other desirable features.

Food Products Industry

Although this industry has received but little attention from electrical engineers, it is the fourth greatest user of electric motors on the basis of connected horsepower. In addition to motors, electric energy is used for various other purposes as the production of ultraviolet rays to help preserve or increase the vitamin content of foods; photoelectric tubes for actuating operations of wrapping, sorting, and counting; cooking of foods by various electrical processes, and the pasteurization of milk.

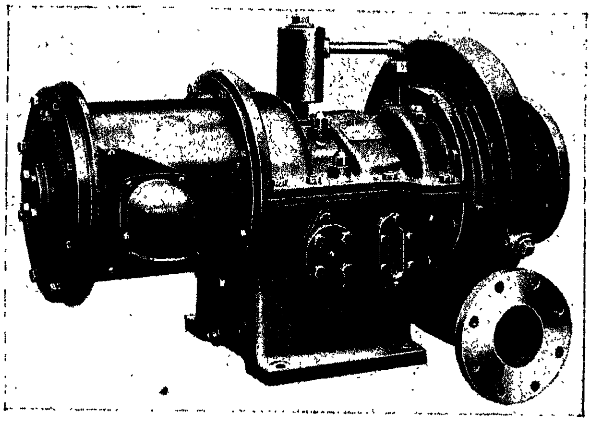

Fig. 7—Geared Centrifugal Refrigeration Compressor Driven by Totally-Enclosed Induction Motor

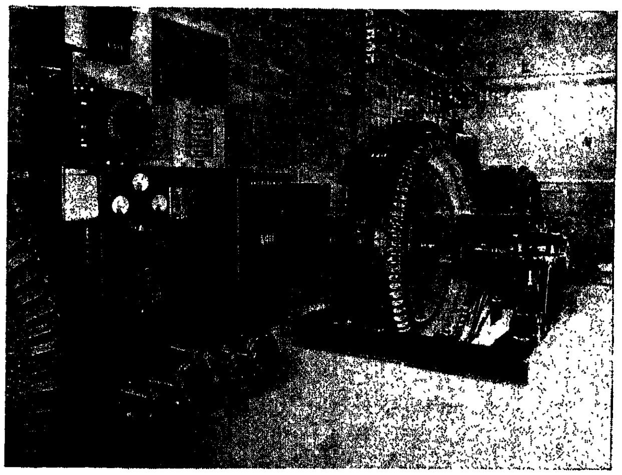

Fig. 8—300-Hp. 164-R. P. M. Synchronous Motor of the Phase-Connected Damper Type as Installed in a Cement Plant

A paper on the subject of *A Modern Electrified Dairy Plant* was presented at the Pittsburgh District Meeting of the Institute March 11-13, 1931, by Mr. A. J. Dreux and Mr. H. C. Brunner. This paper illustrates how a modern electrified dairy offers a very desirable type of load for central stations, particularly when using the electrical conductivity method of pasteurization.

Induction and D-C. Motors

During the past year several new lines of induction motors have been placed on the market and the trend is toward simplification and standardization of design. The greater use of standardized parts reduces the stocks which must be carried both by the user and manufacturer, increases the number of combinations or types of motors possible with a given number of parts and in general makes the apparatus more universally adaptable.

Several new lines of totally enclosed fan-cooled squirrel-cage induction motors have been announced and in practically all cases these motors are on the same frame size as corresponding ratings of open motors. In these fan-cooled motors ball or roller bearings are used almost without exception and the cartridge type of bearing housing is quite generally adopted. This construction permits the dismantling of the motor and the removal of the rotor without exposing the bearings.

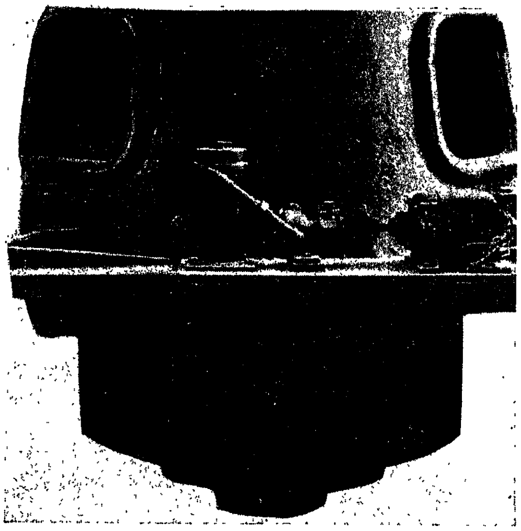

Fig. 9—Special Synchronous Motor with External Revolving Field, Direct Connected to Gyratory Crusher

A number of manufacturers has also brought out lines of totally enclosed fan-cooled motors for use in locations where explosive gases are present. These motors are approved by the Underwriters Laboratory for use in gasoline refining, garages, gasoline handling, and filling stations, dry cleaning establishments, chemical plants, paint factories, and in similar locations.

To meet the requirements of testing large vertical pumps and turbine wheels a vertical dynamometer rated at 300 hp. has been developed. The stator is supported in such a manner that it is free to rotate and the torque developed is measured on a beam and dial scale. The direct-current armature is especially constructed and makes use of a shrink-ring type commutator for high-speed operation.

Fractional horsepower motors of the universal commutator type have a wide speed range from no load to full load and consequently are not generally applicable for the constant speed service. A novel type of clutch has been developed which when installed in these fractional horsepower motors maintains a practically constant speed at the coupling regardless of how much higher the motor speed may go. This device consequently makes it possible to use universal motors for such applications as cash registers, calculating machines, small motor-generator sets, etc.

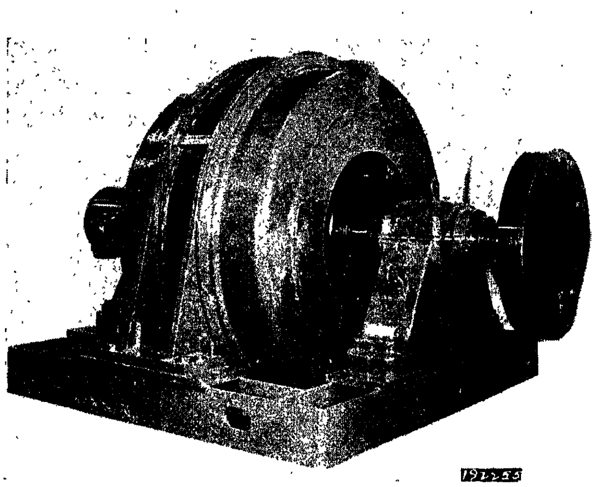

Fig. 10—250-Hp., 450-R.P.M. Totally-Enclosed Fan-Cooled, Synchronous Motor

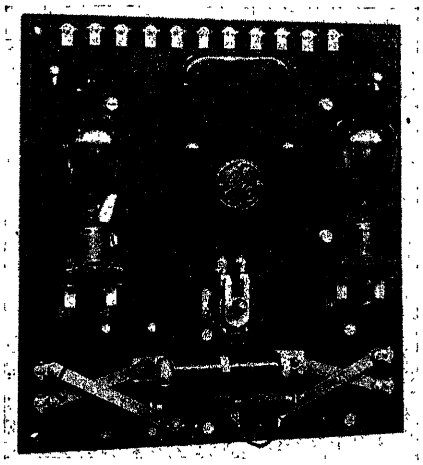

Fig. 11—Electronic Tube Control for Small D-C. Motors

Although speed reducers or gear reducers are now extensively used there is a decided trend towards the combination of various types of these gear reducers with industrial motors in order to form a more compact and self-contained unit. Some of these are of the fixed ratio type with either single, double, or triple reduction while others have a variable ratio. A recent addition consists of a standard constant speed motor in combination with a 4-speed gear forming a self-contained and very compact unit. With this combination various gear ratios are available and it is possible to change from one speed to another under full load conditions.

Another example of a combined unit is a centrifugal type compressor for refrigerating service in which the compressor, gears, and motor are combined in one unit. This is a high-speed single-stage compressor of approximately 25 tons refrigeration capacity and by means of the unit type construction it is possible to eliminate the usual shaft seals.

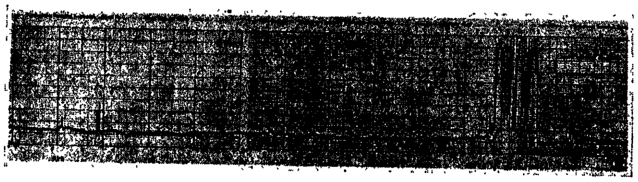

FIG. 12—SAMPLE CHART OBTAINED WITH SMOKE RECORDER

A paper presented by Mr. A. M. Rossman at the Philadelphia meeting *A New System of Speed Control for A-C. Motors,* gives a detailed account of a new method of speed control, its possibilities, and savings. The system consists essentially of a constant speed a-c. motor of either the synchronous or induction type, supplemented by an adjustable speed d-c. machine of much smaller size and a motor-generator set of similar capacity. The frame of the a-c. motor is mounted on bearings so that the frame as well as the rotor may rotate.

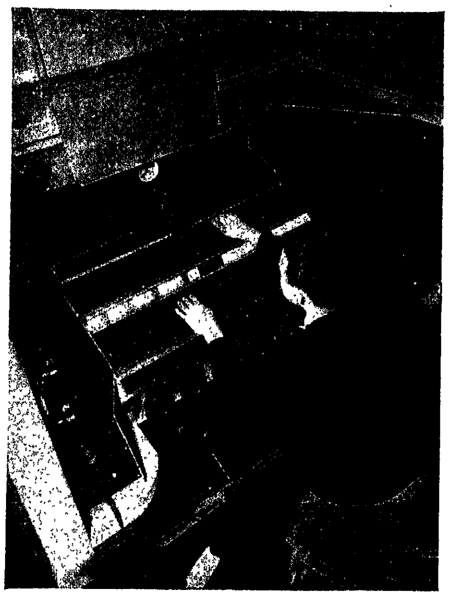

FIG. 13—CONSOLE TYPE BOARD FOR ELECTRONIC TUBE CONTROL OF THEATER LIGHTING AND DIMMING

SYNCHRONOUS MOTORS

At the Winter Convention two papers on the subject of synchronous motors were presented. The motor described by Mr. M. A. Hyde, Jr., was developed especially for low-speed applications requiring high starting and high pull-in torques with a low-current inrush. The damper construction instead of being of the usual squirrel-cage type is phase wound and in starting an external resistance is inserted in this circuit and the motor accelerates in a manner quite similar to that of the ordinary wound rotor induction motor.

The paper presented by Messrs. McLenegan and Ferriss discusses the design features of normal synchronous motors and shows how these features are varied to adapt synchronous motors to the requirements of various special applications. Among the various modifications discussed are the use of part-winding starting for applications where low-starting torques and low-starting inrush are desirable, also various methods of obtaining high-starting torque such as by means of over-sized motors, over-voltage, delta-Y starting, tapped windings, phase-connected damper windings for both salient and non-salient pole motors, and a rotable stator scheme.

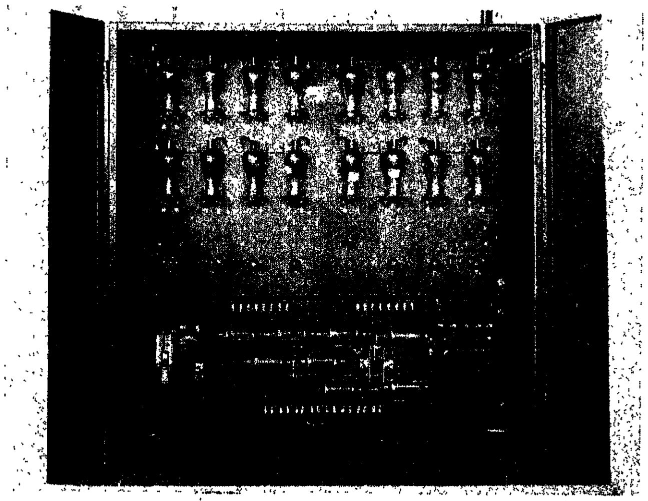

FIG. 14—ELECTRONIC TUBE CONTROL OF POLYCHROMATIC FLOOD-LIGHTING SYSTEM

It is reported that the first application of a synchronous motor directly connected to a grain elevator leg was made during 1930. Ordinarily the starting torque required by these legs or bucket elevators is comparatively light but in case of emergency such as starting after a power failure, with the buckets loaded, a high-starting torque and a high pull-in torque are required.

Although several high-torque synchronous motors have been applied to primary or large gyratory crushers most of these have been of the standard mechanical construction and usually belted to the crusher pulley. A unique application has been made which utilizes a vertical motor of the umbrella type in which the revolving field poles are external to the stator which in turn is bolted rigidly to the frame of the crusher.

Another interesting and rather unusual application of a synchronous motor is for driving a hot copper rolling mill which requires continuous reversing service. The motor is guaranteed to reverse in five seconds and a special type of damper winding construction is used to increase the radiating surface and dissipate heat caused by the frequent starting and stopping.

For use in the Chilean Nitrate Industry a number of synchronous motors rated at 250 hp., 450 r. p. m., was built of the totally enclosed fan-cooled type. This construction is necessary to protect the motors against the saline solutions and vapors and the construction details are along very much the same lines as carried out on the smaller industrial motors.

When protected type motors are required either on account of injurious vapors or dust, it is sometimes undesirable or impossible to locate the control equipment in separate rooms and to take care of those cases in which the control must be mounted in the same location as the motor, synchronous motor starters have been developed with the entire control immersed in a tank of oil.

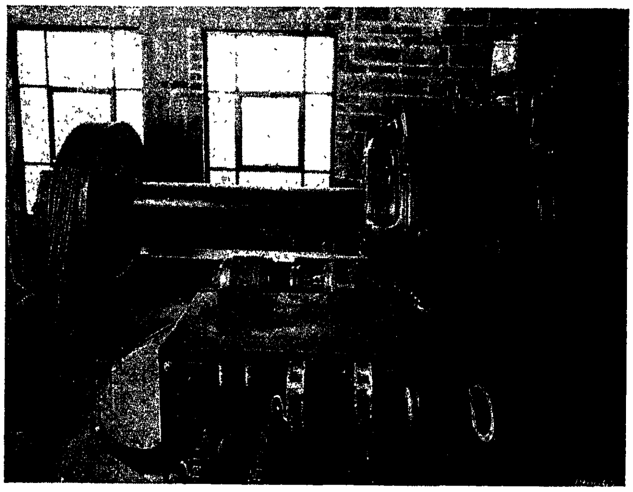

FIG. 15—MOTOR FOR LOWER ELEVATOR OF DUAL SYSTEM WITH COMBINATION MOTOR-GENERATOR SET AND CONTROL FOREGROUND

ELECTRONIC TUBES

During the past year the electronic tube has become an accepted industrial device. Its original use was confined to the arts of communication and science and not until recently has any concerted effort been made to apply it to industrial purposes. Electronic tubes possess characteristics not available in older forms of electrical apparatus but offer many possibilities for industrial applications. These characteristics may be listed briefly as follows: speed of operation, small actuating energy requirement, amplification properties, accurate response, quietness of operation, and freedom from moving parts and contacts. In addition, the actuation of electronic tubes may be brought about by a large number of different physical effects including changes in resistance, inductance, capacitance, phase angle, frequency, temperature, sound, light, color, radio or carrier current.

There has developed a demand for electronic tube units which can be adapted to many applications for experimental purposes. Such units have been brought out by several manufacturers. The more common of these are the photoelectric units and electrostatically controlled arc discharge units. The tubes used in the latter are better known by the trade names of grid glow or thyratron.

In line with this increasing interest a paper entitled *Electron Tubes in Industry,* was presented by Mr. W. R. King at the Winter Convention. This paper gives a general discussion of the theory and characteristics of electron tubes without going into design details or calculations. Several of the more common control schemes involving tubes are explained for the purpose of showing how tube characteristics can be adapted to various applications.

To eliminate the human element in determination of smoke density a device utilizing a light source and photoelectric tube in connection with a recording instrument has been developed and gives a continuous accurate record of smoke density. The light source is mounted on one side of the stack and throws a beam of light through an aperture on the photoelectric tube mounted on the opposite side. The amount of light reaching the photoelectric tube is determined by the smoke density, and indicating or recording instruments may be installed at any convenient location.

One of the most interesting and largest electron tube applications is the control of lighting for stages and auditoriums. Installations of this type involve the use of between 300 and 600 electron tubes. Three installations of this type are in the Civic Opera House in Chicago, the Severance Memorial Hall in Cleveland, and a theatre in Los Angeles. The latest of these units, the one at Cleveland, has all of the control circuits operated from an organ type console. With this control it is possible to pre-set scenes, gradually fade from scene to scene with either manual control or automatically at a pre-determined rate, and vary the intensity of any light circuit in the hall individually or in combination with any other circuit or circuits. In the old types of stage lighting control the intensity was varied by means of rheostats. This new method uses three-legged reactors located conveniently for load distribution and the degree of saturation and consequent change in light intensity is varied by rectified direct current from tubes. Another application for the same type of equipment as used for theatre dimming is the control of building flood lights. On a large number of new buildings the lighting is so arranged that the shading and colors vary in some regular cycle.

Electron tubes are also being used for speed control of d-c. motors in a number of various applications. At the present time for smaller motors, that is 3 hp. or below the control can be accomplished directly by control of armature voltage and current supplied from tubes, while for larger motors the field current only is controlled and supplied by tubes. One of the better known applications of this type is the maintaining of proper tension in the wire for a wire drawing machine and reel.

Photoelectric units have also been adapted to any number of production line applications where the objects are too light or fragile to operate ordinary control making or breaking devices by physical contact. On any application where an object can be made to intercept or otherwise vary a light beam this action can be used to actuate an operation. Some of the more common applications have been for counting, wrapping of packages such as foods, gum, etc., flag switches for reversing rolls as in steel mills, flashover protection of rotary converters, cutting of paper sheets to the proper length as required in connection with paper bag machines, paper break indicators in connection with paper machines, turning on and off lights in factories or offices to give proper illumination without wasting of power, and determining the transparency of paper.

ELEVATOR EQUIPMENT

During the past year numerous improvements and refinements in elevator electrical equipment were made in keeping with the tendency toward higher speeds, automatic landing control, and quieter operation. The common trend toward combination units is also illustrated in elevator apparatus by building of motor-generator sets with exciter and control in one frame.

One of the completely new and interesting developments of the past year was the building of an elevator with two cars operating in one shaftway. Obviously the object of this arrangement is the saving of floor space in tall buildings where the space occupied by elevator shaftways is both valuable and large, inasmuch as the shaftway area must be subtracted from each floor. This elevator embodies all of the latest features in elevator design including automatic floor landing, door opening, and futuristically decorated cars. The cars use the floor bottom system of control and in addition a set of signals are displayed in each car indicating the relative position of both cars in the shaftway. The cars are prevented from approaching each other closer than two floors by an automatic block system of control which brings the car to a normal stop when this limiting distance is reached.

CONCLUSION

The Committee feels that there is a large field open for the electrical engineer in industry and that the Institute can be of material assistance to its members by bringing before them the important developments and trends in the various industries. In the preparation of this report we desire to acknowledge the assistance given by the various members of the committee and also by the Electric Machinery Manufacturing Co.

Instruments and Measurements

ANNUAL REPORT OF COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

THE Committee on Instruments and Measurements has been active during the past year on the following subjects:

1. Standard definitions for telemetering.
2. Standards for recording instruments.
3. Standards for indicating instruments.
4. Revision of Standards No. 14—Instrument Transformers.
5. Revision of Electrical Units.
6. Symposium on precision measurements.
7. Technique of temperature measurements.
8. Measurement of reactive power.
9. Method of measuring distortion factor.
10. Review of proposed papers.
11. Conclusion.

STANDARD DEFINITIONS FOR TELEMETERING

The subcommittee devoted to telemetering has been active for a number of years. Last year in this report there were published for comment standard definitions on this relatively new subject. It has been felt that, with the interest in the field of telemetering, it would be desirable to have some standard definitions so that the terms which are used would not be results from a hit and miss selection, as often occurs in newly developed fields. With comments received this year a set of standard definitions was approved by the membership of the Instruments and Measurements Committee, and is now ready for transmittal to the Standards Committee for adoption.

STANDARDS FOR RECORDING INSTRUMENTS

As a result of several years work, a subcommittee has completed a draft of proposed standards for recording instruments. These standards have been approved by the Instruments and Measurements Committee, and are now ready for submission to the Standards Committee.

The work of the subcommittee is under the chairmanship of Mr. Kinnard. A large amount of work has been involved in the development of these standards so as to cover this field of measuring instruments. The Committee has considered many new items which have shown that the Standards for Indicating Instruments should also be revised.

STANDARDS FOR INDICATING INSTRUMENTS

Since 1927, Instrument Standards No. 23 has been used by the industry. Since that time considerable progress has been made, and experience with the Standards has indicated that a revision would be desirable. A subcommittee was appointed at the beginning of this year to start the revision.

REVISION OF STANDARDS NO. 14—INSTRUMENT TRANSFORMERS

A subcommittee has been active during the past year revising Standards No. 14 covering instrument transformers. This standard was approved in 1925. It was the feeling of the members of the Instruments and Measurements Committee that progress in the art warranted revision at this time. The committee is under the chairmanship of Mr. Gibbs. Several tentative drafts have been prepared and revised so that these standards will soon be in form to be submitted to the Committee membership for approval.

REVISION OF ELECTRICAL UNITS

The report of the Committee on Instruments and Measurements for the Institute year ending July 31, 1929, contained a brief account of the participation of this Committee in the events which led up to the first meeting of the (international) Advisory Committee on Electricity at Paris in 1928. At that meeting resolutions of far-reaching importance were adopted, to the effect that the absolute system of electrical units, derived from the c. g. s. system, may be substituted with advantage for the present international system of units which is based upon arbitrary legalized material standards, namely, the mercury ohm and the silver voltameter.

The second meeting of the Advisory Committee on Electricity was held in Paris in June 1930. The American representative on the Committee, Dr. G. K. Burgess, Director of the Bureau of Standards, was prevented from attending, and sent Dr. H. B. Brooks as his substitute.

Representatives were sent by the national standardizing laboratories of England, Germany, Japan, and the Soviet Republics; by the Laboratoire Central d'Electricite of Paris, and the International Bureau of Weights and Measures at Sevres. Italy was represented by Professor L. Lombardi of the Royal School of Engineers at Rome. Other experts were present as invited guests. A large part of the sessions was taken up with the discussion of a new duty which the International Committee of Weights and Measures had recently laid upon the Advisory Committee on Electricity, namely, that of advising the International Committee on all questions relating to the methods of measurement and to the units and standards of light.

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*COMMITTEE ON INSTRUMENTS AND MEASUREMENTS:

E. J. Rutan, Chairman,
H. S. Baker,
P. A. Borden.
H. B. Brooks,
O. J. Bushnell,
A. L. Cook,
E. D. Doyle,
Melville Eastham,
M. Eppley,
R. O. Fryer,
J. B. Gibbs,
W. N. Goodwin, Jr.,
I. F. Kinnard,
O. A. Knopp,
A. E. Knowlton,
H. C. Koenig,
W. B. Kouwenhoven,
F. A. Laws,
E. S. Lee,
Paul MacGahan,
R. T. Pierce,
W. J. Shackelton.

Concerning the primary standard of light, resolutions were adopted supporting the view that a black-body radiator should be adopted; requesting the national laboratories to examine the specifications for the Waidner-Burgess primary standard of light and to give their views regarding the practicability of its adoption; and urging the desirability of making additional determinations of the brightness of the black-body radiator, especially under the conditions prescribed by the Bureau of Standards' specifications, or at least under conditions comparable with them.

Concerning the unit of light and its maintenance, the Advisory Committee adopted a resolution to the effect that it is inexpedient to change the unit (*i. e.*, the international candle) which has been in use since 1909. Other resolutions adopted relate to the exchange and comparison of groups of lamps by the national standardizing laboratories, and to the adjustment of the values of the practical secondary standards, as may be necessary in the future as a result of reference to a primary standard.

Concerning the electrical units and standards, two resolutions were adopted, as follows:

1. With regard to the unit of resistance, the ohm, considering that methods of determining the absolute ohm are sufficiently advanced and that the agreement between the measurements of the coils (secondary standards) of the different laboratories remains within the limits of precision of the measurements, it is not necessary at present to undertake further comparisons of the resistance coils with mercury ohms.

2. As to the units of electromotive force, on the contrary, the international comparisons of standard cells show differences, exceeding the limits of possible precision, between the values of the electromotive force of the standards of different countries. The committee considers that it is absolutely necessary to make new determinations of the electromotive force of the international Weston cells in each national laboratory by means of the silver voltameter.

The conditions under which the silver voltameter should be used are specified sufficiently in the report of the international committee which met in Washington in 1910. The Advisory Committee recommends, however, that the national laboratories use the Smith or the Kohlrausch voltameter, avoiding organic material, which is detrimental to the electrolytic deposit.

The groups of Weston cells prepared in the several laboratories can be considered as sufficiently constant until the absolute unit of current shall be established.

It should be noted that these recommendations concerning standard cells and voltameters do not in any way modify the Advisory Committee's recommendation of 1928 looking to the ultimate legalization of the absolute ohm, volt, and ampere on a basis free from all arbitrary character. The recommendations merely recognize that the standard cell and the silver voltameter are useful tools, when properly used, and are essential to the maintenance and dissemination of the international electrical units under the existing limitations.

The Advisory Committee also made recommendations regarding the equipment of the International Bureau of Weights and Measures and plans for cooperation between that bureau and the national laboratories in work on electric and photometric standards. Since an international General Conference on Weights and Measures is to be held in 1933, the Advisory Committee decided that it should meet again before that time to study the comparisons of standards which shall have been made and to assign values in absolute units for the standards of resistance and of electromotive force.

SYMPOSIUM OF PRECISION MEASUREMENTS

In view of the recent activity of the International Advisory Committee on Electricity, it was felt desirable to have some outstanding papers written concerning the fundamental electrical units. The subject is being treated in a symposium which is being presented at the 1931 Summer Convention and which includes four papers. These are:

1. *International Standard of Electromotive Force and Its Low-Temperature Coefficient Form*, by Marion Eppley, the Eppley Laboratory, Inc.
2. *The Unit of Electrical Resistance; Past History and Impending Change*, by H. B. Brooks, National Bureau of Standards.
3. *Design of Potentiometers*, by I. Melville Stein, Leeds and Northrup Company.
4. *Electrical Units and Their Application*, by L. T. Robinson, General Electric Company.

TECHNIQUE OF TEMPERATURE MEASUREMENTS

In order to set up a standard code for temperature measurements, a subcommittee has been appointed. This committee has already analyzed all of the temperature requirements included in the various standards of the Institute, and is now summarizing these data preparatory to setting up the necessary measurement technique.

MEASUREMENT OF REACTIVE POWER

Considerable interest is being displayed in the matter of measurement of reactive power. A subcommittee has been considering this subject, and is cooperating with a committee appointed by the

Standards Committee under the chairmanship of Mr. A. E. Knowlton.

METHOD OF MEASURING DISTORTION FACTOR

In line with the recommendation of this Committee, made in last year's annual report, a subcommittee has been following the performance of Belfils Bridge which is being used by one of the manufacturing companies. The work has progressed to the point where a report has been prepared covering the performance of this apparatus. At the present time the report is in circulation among the members of the Instruments and Measurements Committee in order that their comments and recommendations may be obtained in regard to the suitability of this device for the measurement of distortion factor.

PAPERS

In addition to the four papers mentioned above in connection with the symposium of precision measurements, nine papers have been submitted to this Committee for review. Some of these have already been approved for publication and presentation and the remainder are in circulation and will be reported on shortly. These papers are listed below:

Measurements of Cable Insulation Characteristics

A High-Sensitive Power-Factor Bridge, by W. B. Kouwenhoven and A. Banos.

High-Voltage Bridge for Measurement of Cables with Grounded Sheaths, by C. F. Dawes and A. F. Daniel.

The Elimination of an Inherent Error in the Usual Form of Capacitance Bridge for Capacitance and Power-Factor Measurements by the Substitution Method, by R. P. Siskind.

Measurements of Magnetic Flux

Core Loss Measurements at High-Flux Densities, by B. M. Smith and C. Concordia.

This paper was presented at the Northeastern District Meeting, Rochester, N. Y., April 1931.

Miscellaneous Subjects

A Direct-Current Bushing Transformer, by A. S. Fitzgerald.

A New Overcurrent Relay with Straight Line Characteristics, by S. L. Goldsborough and R. M. Smith.

A Thermionic Type Automatic Synchronizer, by F. H. Gulliksen.

The Characteristics of the Oscillograph-Galvanometer, by V. S. Thomander.

The Amplifier-Oscillograph, by S. K. Waldorf.

CONCLUSION

Active interest has been shown by the members of the Committee on Instruments and Measurements through the year. The meetings held were well attended and subcommittee reports indicated considerable progress was being made in each of the assigned activities, and definite steps have been taken on several as indicated above. During the coming year it is expected to complete some of the other projects.

Applications to Iron and Steel Production

ANNUAL REPORT OF THE COMMITTEE ON APPLICATIONS TO IRON AND STEEL PRODUCTION*

THE functions of this committee have, in the past, been largely confined to (1) encouraging the presentation of papers before the Institute dealing with those phases of electrical engineering which are major factors in the utilization of electricity in the steel industry. (2) To preparing an annual report which briefly summarizes such phases of the application of electricity to the production of iron and steel as are considered new or of special interest to the membership.

During the past year, the committee's work has followed the previous precedent, in procuring papers. It also actively cooperated in arranging a joint session of the Institute with the Association of Iron and Steel Electrical Engineers at the meeting of the Middle Eastern District held in Pittsburgh on March 11th to 13th inclusive, 1931. The papers presented before this meeting which the members of this committee were active in procuring are as follows:

1. "Conversion and Distribution of General Purpose D-C. Power in Large Industrial Plants," by R. D. Abbiss, Carnegie Steel Co., and D. C. West, Westinghouse Elec. & Mfg. Co.
2. Symposium on Interconnection Between Utilities and Industries: Davison Coke and Iron Co. and Duquesne Light Co. Interconnection, by G. E. Dignan, Davison Coal and Iron Co. and R. L. Kirk, Duquesne Light Co.
3. "Interconnection of Power Supply Between Public Utilities and Large Industrial Users," by F. O. Schnure, Bethlehem Steel Co.
4. "Absorption of By-Product Power," by A. Hoeffle, Toledo Edison Co. and W. T. Woodmancy, Interlake Iron Corp.
5. "The Use of Electricity in Large Annealing Furnaces," by J. C. Woodson, Westinghouse Elec. & Mfg. Co.

The Committee wishes to report that this joint meeting of the Institute and the Association of Iron and Steel Electrical Engineers was a very successful part of the Middle Eastern District Meeting Program, and suggests that joint meetings with the Association of Iron and Steel Electrical Engineers be encouraged in the future.

ELECTRICAL DEVELOPMENTS IN THE IRON AND STEEL INDUSTRY DURING 1930

During the year 1930 there has been a general recession from the unusually high operating rates of the preceding year, and an accompanying reduction in expenditure for improvements and new plant facilities. However, an impressive amount of electrical equipment has been purchased and many interesting developments have taken place. Undoubtedly, the very successful electrification of rolling mills and their auxiliaries has been an important factor in the steel industry.

The iron and steel industry during 1930, purchased 163,490 total horsepower of main drive motors, rated 300 hp. or over, as compared to a total of approximately 350,000 hp. during 1929. The fact that the rate of increase in installed horsepower for main drives is greater than the rate of increase for ingot capacity, indicates the tendency to modernize old mills.

Direct-Current Motors

Many important installations have been completed during 1930, with others rapidly nearing completion. From various viewpoints, a new 10,000-hp., 54-inch blooming mill in the Chicago District is memorable. It is the most powerful mill yet installed by a margin of 2,000 hp., an increase in power which will be useful in rolling thicker and heavier sections. This tends toward greater output of the whole plant, the blooming mill being the first of all the rolling operations.

Even more than for its size, this mill is unique in that the two main rolls, usually geared together, are driven individually, each by its own motor. This is a great improvement over the former method of a single motor coupled to a pinion stand. The ordinary construction of mill pinions and housings permits wear and misalinement from which develop accelerated wear, noise, vibration, and occasional breakage. Often the mill must continue in operation for several days after trouble has been developed before it can be conveniently shut down.

Each roll of the new 54-inch mill is driven by a double armature motor rated at 5,000 hp., 700 volts, direct current, at 40/80 r. p. m., both motors being under electrical control which keeps the speed of the two rolls precisely the same. The torque developed is 4,000,000 lb-ft., from standstill up to normal speed. The motors are of minimum diameter to avoid angularity of the mill spindles between motor and rolls, an incidental advantage being smaller inertia.

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*COMMITTEE ON APPLICATIONS TO IRON AND STEEL PRODUCTION:

A. C. Cummins, Chairman,
F. B. Crosby,
M. M. Fowler,
S. L. Henderson,
A. M. MacCutcheon,
A. G. Pierce,
F. O. Schnure,
W. B. Shirk,
G. E. Stoltz,
Wilfred Sykes,
T. S. Towle,
H. A. Winne.

Immediately following the 54-inch blooming mill just referred to is the 52-inch beam mill. The roughing mill is driven by a 7,000-hp. reversing motor, and a 2,000-hp. reversing motor for the edging stand. Likewise the intermediate mill will be equipped with reversing motors rated at 6,000 hp. and 2,000 hp.

There is now under construction by this same company, a 44-inch universal slabbing mill, the driving motors of which will have a continuous capacity of 12,500 hp., and a maximum emergency capacity of 35,000 hp. The upper and lower horizontal rolls are to be individually driven by two 5,000-hp., 40/80-r. p. m. reversing motors, constituting a twin motor drive of 10,000 hp., 4,000,000 lb-ft. maximum torque capacity, duplicate of the 54-inch blooming mill now in operation. The vertical edging rolls are to be driven by a third reversing motor, rated 2,500 hp., 79/225 r. p. m., 500,000 lb-ft. maximum torque capacity. Power for the three reversing motors will be furnished by a 10,500-kw. flywheel motor-generator set consisting of a 180,000-lb. flywheel, a 6,500-hp., 25-cycle, 6,600-volt, 370-r. p. m. induction motor, and three 3,500-kw., 700-volt generators connected in parallel. This installation will be of unusual interest to steel mill engineers because of the large size of the mill and the electrical equipment, and also because of the method of drive, utilizing three reversing motors with control to provide adjustment of relative speeds, thus permitting variations in drafting and the use of rolls of unequal diameter.

To secure the necessary refinement for the accurate automatic control of the screwdown mechanisms on a 32-inch three-high universal plate mill and on roughing and intermediate 52-inch universal structural mills, seven variable-voltage screwdown equipments have been installed. The variable-voltage control permits much more accurate settings than could be obtained with rheostatic control, either automatic or manually operated, and thus speeds up the operation of the entire mill. A further advantage is the elimination of the large capacity reversing and accelerating contacts and starting resistor, with accompanying lowered maintenance.

In addition to the 54-inch and 44-inch mills referred to above, this company is also completing a 96-inch continuous plate mill, a 10-inch alloy bar mill, a large open-hearth department, and a 20,000-kw. addition to the existing steam turbine power station.

The 10-inch alloy bar mill will be driven by nine direct current motors, totaling 7,627 hp. Some of the motors have a speed range of approximately 5 to 1, which is obtained partly by motor field adjustments and partly by armature voltage control through the use of auxiliary bucking generators, one for each of two motors which have this large speed range. The use of these bucking generators permits operating the three main 1,750-kw., 600-volt generators in parallel at constant bus voltage. The motors will be equipped throughout with speed regulators of the vibrating type, designed to hold the speed regulation within very close limits.

An 8,000-hp., 40/100-r. p. m. reversing motor is now being built to drive a 44-inch blooming mill at Gary. This motor will be capable of developing a maximum torque of 2,900,000 lb-ft. The mechanical parts of this motor, including the armature spider, will be of fabricated steel construction throughout. Several reversing motors with fabricated and electrically welded armature spiders have been in service for some time, demonstrating beyond doubt the reliability of this type of construction. Power for the 8,000-hp. motor will be supplied by a 375-r. p. m. motor-generator set, consisting of two 3,500-kw. generators, one 6,000-hp., 6,600-volt, 25-cycle induction motor, and one 200,000-hp-sec. flywheel.

A southern steel company has placed in operation at Alabama City, a new 40-inch blooming mill which replaces an engine-driven 36-inch mill. The 40-inch mill is driven by a 7,000-hp., 700-volt, 50/120-r. p. m., single-armature reversing motor supplied with power from a 6,000-kw. flywheel motor-generator set. This company has also installed a new 32-inch three-high universal plate mill driven by a 4,000-hp., 80/160-r. p. m., d-c. motor, similar to a reversing mill motor, with variable-voltage power supplied by a 3,200-kw. flywheel motor-generator. The major part of the mill output is light gage sheets. The type of drive used permits the operator conveniently to select low speeds for the roughing passes, and high speeds for the finishing passes, with very rapid acceleration to the desired rolling speeds. An important feature of this mill is the automatic screwdown. When the operator moves the pass master switch to each successive position, the desired screwdown setting for each pass is obtained by automatic control.

A 20-inch continuous hot strip mill in the Detroit District was put into operation in 1930. This mill has ten stands, each driven by an individual d-c motor. The drive for this mill has one very interesting feature. When rolling from slabs of such length that the piece will reach from stand 4 to stand 5, the section of the bus to which the first four motors and one 5,000-kw. generator set are connected, is segregated from the bus to which the remainder of the motors and the other generators are connected. This is necessary because the minimum speeds of the first four motors when operating at normal rated voltage are such that the metal would be delivered from stand 4 at a very much higher speed than it enters stand 5. Consequently, when the piece is continuous between stands 4 and 5, the speeds of the first four stands must be lowered by reducing the voltage of the generators on the section of bus to which the first four motors are connected. A similar arrangement was incorporated in the control of the first two motors on the 60-inch strip mill in a plant at Steubenville, Ohio.

Motor drive has for the first time been successfully applied on a large scale to the operation of a 900-ton ingot pressing application that was formerly monopolized almost entirely by steam or hydraulic operation. This press is in the new plant of a wrought iron manufacturer near the Pittsburgh District and compresses wrought iron sponge balls, about five feet in diameter, into rectangular ingots, measuring about 6 ft. by 18 inches square, preparatory to rolling in the blooming mill. On the final squeeze, it is necessary to exert a pressure of at least 1,000 pounds per square inch. Maintenance of factory production at full speed, requires operating the rams up to 75 feet per minute. Still the motors and press must be protected from the enormous stress which would result if the ram was brought up suddenly against a solidly compressed ingot. The solution of these and other problems involved a coordination of generator, exciter, and motor characteristics with manual and automatic control facilities, so that, as the pressure increases, the ram speed is slowed up towards the end of its stroke and the current will never exceed the allowable limit.

The main 900-ton ram is driven, through four racks and eight pinions, by a double-armature, 1,200-hp., d-c. reversing motor, having a normal full-load speed of about 125 r. p. m., and a maximum light-load speed of 275 r. p. m. The motor was built with two armatures in order to reduce the $W R^2$ and to halve the current to be carried by each commutator. The auxiliary 200-ton end rams are driven by a 325-hp. single-armature motor, having a nominal full-load speed of 250 r. p. m. and a maximum light-load speed of 550 r. p. m. The motors are of sturdy mechanical construction, with cast steel armature spiders, special armature coil bracing, and thrust bearings at the coupling end. Rear enclosing end bells are provided so that the motors may be ventilated. This is necessary as the motors carry heavy loads at very low speeds, and are therefore incapable of self-ventilation.

Variable-voltage d-c. power for the two press motors is furnished by a four-unit synchronous motor-generator set, consisting of a 1,000-kw. generator for the large motor, a 300-kw. generator for the small motor, a 1,500-hp., 80 per cent power factor, 6,600-volt, three-phase, 60-cycle, synchronous driving motor, and a 50-kw., 250-volt exciter.

In addition to the electrical features enumerated, the mechanical design of the press incorporates a number of features intended to provide safe and reliable operation. The faces of the main ram head and stationary side stop are not smooth but have corrugations vertically and horizontally across them, so that on the first impact, only about 10 per cent of the total face of the ram strikes the ingot and the ram has to move in about 1½ inches before the entire face strikes.

The electrically driven press has been in operation several months, and its success has demonstrated the practicability of electrical drive for such machines.

A mill in the Youngstown District has purchased the electrical equipment for a 10-inch bar mill having 12 tandem stands. Ten d-c. motors totaling 7,350 hp. with variable-voltage control from two 2,000-kw. motor-generator sets will be used with this mill. The mill will have two unique features, one being the method of speed control and the other is the use of vertical motors to drive the vertical roll main stands.

A speed regulator of the carbon pile type is used with each motor and with a master frequency generator to maintain a desired speed relation between stands. The customary bevel gear drive to the rolls has been eliminated by the use of vertical motors. The vertical motor is mounted above the mill on an overhung support. This support also carries the rolls and pinion housing. The rolls can be moved sideways or up and down with respect to the bar being rolled so that the vertical rolls can be lined up with the grooves of the horizontal rolls.

Synchronous Motors

Among the more important synchronous motors which have been purchased during the year may be mentioned two 4,500-hp., 156.5-r. p. m., 6,600-volt, 60-cycle units which will drive two rolling mills in the plant of a Pennsylvania manufacturer. This company also purchased one 5,000-hp., 360-r. p. m., 6,600-volt synchronous motor to drive a 24-inch billet mill and one 4,000-hp., 360-r. p. m., 6,600-volt motor to drive a 28-inch billet mill at the same plant early this year. This company put into operation a 3,000-hp., 100-r. p. m., 11,000-volt, three-phase, 60-cycle synchronous motor, driving a three-high billet mill. This motor is of interest not only because it is one of the few main roll motors operating at over 6,600 volts, but also because it is started directly from the 11,000-volt circuit.

A West Virginia manufacturer has purchased two synchronous motors, one 2,000-hp., 300-r. p. m. and one 1,000-hp., 360-r. p. m., which will drive the hot tin mills. This is believed to be the first installation of synchronous motors on mills of this character, previous practise having been to use induction motors with flywheels. Synchronous motors were chosen because of the necessity of maintaining a good power factor, and also because of the gain in efficiency. Not only is the synchronous motor itself more efficient than the corresponding induction motor, but the friction and windage losses of the usual flywheel and the power losses in the secondary resistor or liquid slip regulator are eliminated. It is estimated that the power per ton of tin plate rolled will be at least 5 to 10 per cent less than if an induction motor flywheel drive had been used.

Switchgear

All the modern improvements in switchgear equipment are rapidly being adopted by the iron and steel industry. The metal clad type of switchgear with its live parts completely enclosed, excluding dust and dirt and at the same time protecting the operator from possible injury, is ideally suited to steel mill service.

Auxiliaries

Automatic screwdown equipment has been developed to the point where it will rapidly become more generally used. Two recent applications, one in a universal plate mill and the other in a structural mill have been mentioned in this article. The use of variable-voltage equipment for these screwdown drives has proved very desirable.

There is increasing industrial activity in the application of vacuum tubes and related devices. The crane operator on the soaking pit cranes for a 54-inch mill in the Chicago District will control the opening and closing of the soaking pit covers through the action of photoelectric cells. In another plant, a photoelectric cell acts as a "flag" switch to make the necessary set-up for registering the temperature of each billet as it approaches the rail mill. Undoubtedly, the field for such applications will rapidly increase.

The majority of the motor-driven heavy shears, such as bloom and slab shears, which are now in operation, are driven through clutches by induction motors equipped with flywheels. The mechanical clutches are a source of more or less trouble, and to eliminate these and also the losses in the continuously running motor and flywheel, several shears have recently been installed with d-c. motor drives, arranged to start and stop with each cut.

Two of these are in a new plant near Detroit. The larger of the two is an 800-ton slab shear, designed to cut a slab 8 inches thick by 25 inches wide. Another midwestern steel plant has recently placed in operation eight shears, cutting cold stock up to a maximum of ¼ inch thick by 42 inches wide. Some idea of the high rate of acceleration and retardation may be obtained from the fact that the shear makes a complete cycle in less than one second, and during this time the motor starts from rest, attains a speed of over 450 r. p. m., cuts the plate and stops.

A Pittsburgh tube mill has installed two scrap shears for crushing and shearing pipe up to 24 inches. They are of the new type with the shear motors starting and stopping for each cycle.

What is believed to be the first application of synchronous motors to flying shear drive is in connection with a 20-inch hot strip mill in the Detroit District. The shear is of the rotary flying type, and, to insure that the metal shall be cut into equal lengths, it is necessary that the speed of shear be synchronized with the delivery speed of the metal from the mill. To accomplish this, an a-c. generator is provided on each stand, from which the metal may be delivered. The shear is driven by a synchronous motor, the power for which may be obtained from any of the a-c. generators.

Three ore unloaders recently placed in operation at one of the Lake Erie Docks are interesting on account of their large size. The combined capacity of the three unloaders is 3,600 tons per hour, and the actual time for unloading a 10,000-ton boat is four or five hours. The bucket capacity for each unloader is 17 tons. Each unloader uses eight motors totaling 1,060 hp. The beam hoist motor is a 350-hp., 500-r. p. m., shunt-wound mill motor and the trolley travel motor is a 170-hp. motor, these two motors having variable voltage control. The bucket closing and opening motor is a two-speed wound-rotor mill type motor, and all other motors are a-c. motors. The motor-generator set for the variable-voltage control is mounted inside the beam and serves to help balance the stiff-leg weight.

As electrical improvements in the iron and steel industry are reviewed each year, the opportunities that exist for improvements in steel mill drives and auxiliary equipment become increasingly evident. These improvements will result from a close cooperation between the steel plant engineer, the mill builders, and the engineers of the electrical manufacturer.

Production and Application of Light

ANNUAL REPORT OF THE COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT*

Production of Light

Statistics on Incandescent Lamp Sales

THE sale of incandescent lamps held up remarkably well during the past year, large lamps showing a decrease of about 1 per cent as compared with 1929. The Central Station revenue derived from the two classes of service in which light is a large factor (domestic and commercial, small power and light) showed an increase of about 7.5 per cent as compared with the previous year, offsetting the reduction from other uses of electricity, and leaving a net increase of about 3 per cent.

The average lumens, watts, and efficiency of the large lamps sold last year all increased as compared with the year before. The average lumens went from 797 to 814; the average watts from 60.7 to 61.2 and the average lumens per watt 13.1 to 13.3.

Of the sixteen standard wattages from 10 to 1,000 inclusive, used in multiple service, three sizes 60, 100, and 200 watts, represent nearly half (46.6 per cent) of the total wattage demand.

The percentage of 110-volt and 115-volt lamps sold decreased slightly, while that of 120-volt gained as compared with the previous year. The percentage distribution for last year for 110-, 115-, and 120-volt lamps was 5.2 per cent, 48.9 per cent, and 41.3 per cent respectively. Lamps for 200-250-volt service decreased from 3.3 per cent to 2.6 per cent of the total quantity sold for multiple service.

The demand for street series lamps is concentrating on the 6.6 ampere rating. This now represents 71.2 per cent of the total; the next largest demand being 14.6 per cent which is for the 15- and 20-ampere compensator type lamps.

New Sources of Ultraviolet Radiation

A new type of lamp (called a glow lamp) has been developed which produces ultraviolet light by virtue of a glow discharge through mercury vapor between two hot cathodes of the oxide coated type. The two heater filaments for the cathodes are connected in series and their resistance produces a sufficient difference in potential to cause a discharge between the two cathodes, once they have become heated. The lamp is rated at 2 amperes and 18 volts. This lamp, designed for operation on alternating current requires a starting potential of some 35 volts, after which 18 volts is sufficient to maintain the discharge. One, two or three lamps may be operated on the ordinary 115-volt lighting circuit in connection with a suitable current-limiting resistance, reactance, or transformer. The glass bulb has been selected for its transmission characteristics so that the lamp will produce practically no radiation below 2,800 Angstrom units. In addition to producing the desirable radiations of ultraviolet light, it also produces blue and green light in the visible spectrum which may possibly be used to advantage in the future to supplement the light of Mazda lamps, to secure a nearer approach to a light subjectively white in color as well as to obtain the healthful ultraviolet radiation.

In last years report a new tungsten-mercury arc lamp was referred to. This lamp consumed about 315 watts. A lamp of the same general characteristics, but of about forty per cent of this wattage has recently been announced. The bulb is smaller, and is fitted with a metal cap which raises the operating temperature and pressure of mercury vapor in the bulb, and increases the efficiency of production of ultraviolet radiation. The ultraviolet output of the new lamp is approximately one-half of that of the older one. The transformer to be used with the new lamp weighs about 7½ pounds and is small enough so that it can easily be embodied in the design of fixtures, to permit a wider use of this type of lamp, especially a source for dual lighting service.

Still another type of lamp employing a tungsten filament, operated at a high temperature has been found to produce ultraviolet radiation in the biologically active range in sufficient quantity to be of value at least to poultry and animals where exposure times are not too short. Lamps for such service must, of course, be made with special bulbs which will transmit this radiation, and two sizes, 60 and 500 watts for operation on standard lighting circuits have been made available.

A powerful, long-burning type of carbon arc has been developed for the production of ultraviolet radiation which was described in an illumination item in the December issue of the A. I. E. E. Journal, page 1031.

Gaseous Conductor Sources of Light

An arc, in an atmosphere of krypton and sodium, has been described by Dr. M. Pirani.* This operates in a tube about one inch in diameter and 35 inches long which has to be maintained at a temperature of 350 deg. cent. (somewhat above the melting point of lead). A very high efficiency, about 70 per cent of the theoretical maximum, is obtained based on the input to the arc alone. With the supplementary heating required, the over-all efficiency would, of course, be reduced. Previous to this time sodium arcs with efficiencies of from 50 to 70 lumens per watt have been described. The light from such lamps, however, is nearly monochromatic and would, alone, be of limited utility for ordinary lighting service.

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*COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT:

G. S. Merrill, Chairman
J. W. Barker,
A. E. Bettis,
W. T. Blackwell,
H. S. Broadbent,
J. M. Bryant,
W. T. Dempsey,
E. E. Dorting,
L. A. Hawkins,
H. H. Higbie,
W. C. Kalb,
C. L. Kinsloe,
R. D. Mailey,
P. S. Millar,
C. J. Stahl,
G. H. Stickney.

Dr. Pirani has also obtained great increases in brilliancy in mercury and in neon discharge tubes.†

The combination of hot cathode neon and mercury vapor lamps to produce light apparently white in color, at a high efficiency, (mentioned in our report for 1928) is again attracting interest, as is also the combination of the mercury arc with incandescent lamps.

Small Gaseous Conductor Lamps

These small negative glow lamps used for night lamps, indicative and current detectors, are now designed to operate on line voltages from 90 to 130, and to consume from 0.01 to 2 watts,. The former is merely an indicator, the latter gives a maximum normal candlepower of 0.2.

Photoflash Lamp

A lamp has been designed to produce a high intensity flash for use in photographic work, consisting essentially of crumpled aluminum foil in an atmosphere of oxygen, which is ignited by a small filament that can be operated on any voltage from 2 to 130. It is made in a bulb of the size and shape of the 100 watt lamp used for general lighting service.

The flash lasts approximately 0.02 second, the radiation is about such as would be obtained from a black body at a temperature of 4,000 deg. K. The flash is equivalent in candlepower to about 250 ordinary 500-watt lamps. It is noiseless and fumeless, the products of combustion being retained within the bulb. The lamp is finding wide use in the photographic field.

40-Watt, Gas-filled Lamp

The 40-watt lamp for ordinary lighting service is being changed from a vacuum to a gas-filled type, and, at the same time put in a slightly smaller bulb. The initial efficiency of the new lamp is slightly higher, and the light output is maintained better throughout life.

50-Watt Lamp

The 50-watt incandescent lamp, for general lighting service, has been removed from the regular schedules of the manufacturers of Mazda lamps. Its demand can apparently be shifted largely to the 60-watt size which is gaining steadily in popularity. The three sizes, 40, 50, and 60 represented unnecessarily close steps.

New Incandescent Lamps

Three new lamps for 110-, 115-, and 120-volt lighting service have recently appeared on the market. These are, a 5-watt lamp in a bulb ¾ inch in diameter, a 100-watt in a tubular bulb 34 inches long, and a 150-watt in a tubular bulb about 12 inches long.

APPLICATION OF LIGHT

Ultraviolet

The utility of ultraviolet radiation for purposes, other than merely the prevention of rickets, has been attracting wide attention and has been the subject of much experimental work. Its most promising physiological benefits seem to lie in the direction of prevention of colds and relief of anaemia. In the industrial field powerful carbon arcs are used for making accelerated tests (which must however be carefully evaluated) and for the treatment of food, tobacco, and other products. Small incandescent sources can be used in poultry houses with good effect.

The use of screens with arc sources to absorb the ultraviolet radiation shorter than that which it is desired to use, has grown during the past year, particularly in outfits intended for use in the home. A time limit switch is also incorporated with some outfits to reduce the probability of over-exposure. The development of very powerful arc sources with long-burning carbons, has extended the possible use of ultraviolet radiation in both industrial service, and in treating large groups in hospitals and sanatoriums.

Trends in Lighting Practise—1930

The interest of architects and decorators in the use of artificial light as a component part of their decorative scheme, is becoming more and more widespread. At first the new ideas were accepted in only the larger cities, now in most of the smaller cities and larger towns excellent examples of the new practise can be found.

Instead of trying to imitate flame sources, candles and oil lamps in fixtures intended for rooms of classical treatment, the skillful designer produces a luminaire which serves the modern light sources in an effective manner and then incorporates in the detail of decoration elements which are inherent to the decorative period under consideration.

The more commercial or stock fixtures which have appeared on the market during the last few months exhibit a tendency to new forms, characterized in general by simplicity of line and pleasing proportions.

If satisfactory illumination is to be obtained from side wall outlets, these must be fitted with some sort of device quite different from the ordinary candlestick bracket. Manufacturers are beginning to realize the possibility of so-called semi-indirect, side wall pockets or urns and a number of interesting varieties have been placed on the market during the period under consideration.

Only a few years ago it was the practise to finish the building and then choose the lighting fixtures. As a

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**Zeitschrift fur Technesche Physik*—Nov. 1930.

†*E. T. Z.*,—June 1930.

result they often tended to appear as an incongruous after-thought, and not a component part of the structure. We are now seeing many instances of what has been termed "built-in" lighting, but these arrangements cannot be carried out unless suitable provision is made in the initial plans for the placement of lighting equipment.

There is a growing appreciation of the value of light to look at (as well as to see by) and in the more modern buildings we see interesting installations of luminous panels, niches, and touches of color which give no useful illumination but are pleasing to the eye.

Naval architects and ship owners realize that their vessels must be made more interesting from a decorative standpoint if they are to attract patronage under conditions of severe competition, and decorative lighting is receiving more attention than ever before in marine service.

There seems to be a trend in commercial lighting practise toward the greater use of indirect lighting equipment, both semi-indirect and totally indirect. Such forms of lighting which are desirable for general use in commercial interiors have been rather slow in being adopted probably because they require better maintenance than the enclosing globes.

Technical progress has been made in practically every field of lighting. In some of the newer ones, such as lighting for outdoor sports and for aviation, there has, in addition, been a very rapid growth. There have been no revolutionary changes, however, in equipment and methods generally employed.

Windowless Buildings

Perhaps the most outstanding development in connection with the use of daylight or artificial light for buildings that has taken place to date was started during the past year. The new factory of the Simonds Saw & Steel Company, Fitchburg, Mass., which is now nearing completion is built entirely without window openings. This pioneering project is receiving much publicity and the results will unquestionably be watched with interest and have a distinct bearing on the future building construction. In this building lighting units consisting of a combination of mercury vapor tubes and tungsten filament lamps will be used to secure a subjectively white color of light. Some of the tubes will be of ultraviolet transmitting glass to provide the desired amount of such radiation. Another notable example of this nature is the Parker Bridget Department Store in Washington, D. C. This store depends entirely on artificial illumination for its operation. It is felt that by eliminating windows lighting conditions are constant at all times. It is much easier to accurately control temperature and ventilation. Then, too, from a merchandising standpoint the larger percentage of wall area is available for display space.

With the record for continuity of service which has been attained by the central stations, and the development of effective means of lighting, ventilation and air conditioning, windows are no longer essential. There are so many advantages to be gained by their elimination in certain classes of use, that it appears as though this subject will receive increasing attention in the future.

Proper Operating Voltage

The N. E. L. A. Lamp Committee gives in its report this year, the results of further surveys of socket voltages, which show some improvement in the average value as compared with the sample cities studied the year before. The spread in voltage, however, shows no improvement. The results given in these surveys apply particularly to residential service. In large office buildings and industrial plants the average socket voltage is probably relatively lower than in residential service because of the greater voltage drop in interior wiring.

The N. E. L. A. Lamp Committee Report for 1928 contained a summary of data on operating voltages as reported in use for some 18,000 communities. This summary showed that 5.4 per cent of the population considered was in communities served at more than one standard voltage. Five years earlier the percentage had been 13.2. This trend toward the use of one standard operating voltage in each community aided in putting lamps of correct voltage in service, because, it is obviously difficult, if not impossible, to avoid mixing voltages in service where two or more standards are in use. The maintenance of but one standard service voltage throughout a community makes it much easier to be sure that lamps of only the correct voltage are used, and this is important from the standpoint of lighting service in general.

Minimum Wiring Specifications

In addition to the minimum specifications for the adequate wiring of lighting circuits in commercial and public structures, mentioned in last years report, specifications covering industrial and residential service will soon be made available as a result of further work by N. E. L. A. Committees. All of these specifications are in such simple form that they can be used with the greatest ease. They provide minimum standards to which all new buildings should conform in the interests of good lighting service. We again recommend that every electrical engineer who is brought into contact with the design or operation of lighting installations should be familiar with these specifications.

Stroboscopic Developments

A new type of stroboscope has been developed in which the discharge characteristics of a three-element grid glow tube are utilized in conjunction with a condenser to produce the brilliant flashes of light of exceedingly short duration and high frequency needed in such work. Another method, described in German technical literature produces flashes of the desired character by the combination of motion of three disks carrying different numbers of radial slits. A more complete description of these devices has been submitted for publication as an Illumination Item.

Group Replacements

The replacement of incandescent lamps in street lighting service in complete groups rather than individually as failures occur, offers a possible means of securing a higher general level of illumination and reducing the number of outages at no increase in operating cost. It is being used, or tried out, in a number of localities. If the burning hours of all the lamps in a large group are identical, and if the cost of replacing lamps individually as they burn out is relatively high, it may be advantageous to replace the entire lot as soon as the burnouts begin to occur with some frequency, which will ordinarily be at the time the lamps have attained about 70 per cent of their average life. If this general replacement is made to coincide with one of the periodic cleanings of the lighting equipment the replacement cost per lamp is relatively small. This same practise might well be applied in other classes of service, where the cost of making individual replacements is relatively high, and where all the lamps in a large group burn the same length of time.

Fixed Focus Automobile Headlights

It has long been recognized that one of the greatest factors contributing toward glare from automobile headlights has been the fact that the lamp filaments were not properly focused in the reflectors. Although the system of approval of headlight equipment by the motor vehicle authorities of the various states after laboratory test has become quite general and all cars are equipped with head lamps capable of producing adequate road light with minimum glare, it has been impossible to keep these equipments in proper adjustment in the hands of the public. The motorists may learn to aim the headlight beams properly, but the more intricate operation of focusing the filament in the reflector has proved a stumbling block.

Because improvements in lamp manufacture now permit more accurate location of the filaments with respect to the lamp base, and because headlight reflector and lens combinations have been designed that are less sensitive to focal adjustment, it has become possible for the motor vehicle authorities to approve the use of so-called "fixed focus" headlamps from which the focusing mechanisms are entirely eliminated. The sockets in these headlamps are rigidly fastened in the reflectors and the filaments in the lamps of any reputable manufacturer in this country are accurately designed to fit them so that an acceptable beam can be secured by simply inserting the lamp in the socket.

Headlamps of this type are already being used by several of the motor car manufacturers and improvements in the general headlight situation are to be expected as their use becomes more widespread and cars with the old types of equipment are gradually replaced on the highways.

GENERAL

Present Status of Candlepower Standards

While the needs of practical photometry have been met reasonably well for many years by the expedient of establishing units of candlepower maintained by means of electric incandescent lamps, this procedure does not give a permanent solution for the problem of photometric standards. There remain unsettled three major difficulties: 1. Several countries, particularly Germany and Austria, still use the Hefner unit, which is 0.9 of the unit recognized by the International Commission on Illumination; 2. no reproducible primary standard has been accepted as representing the international unit which was established for carbon-filament lamps; 3. no specific method has been agreed upon for passing from the carbon-filament lamps to those giving light of other colors.

These difficulties have resulted in discrepancies between measurements made in different countries. The differences are large enough to be very serious in such precise measurements as are made in rating and testing incandescent lamps. Consequently efforts have been made for several years to find a basis for a comprehensive international agreement on this subject. These efforts have been furthered by discussion at several sessions of the International Commission on Illumination. In order to give a more definite legal status to the negotiations the International Committee on Weights and Measures decided in 1929 to take up the problem of photometric units and standards, collaborating with the Commission on Illumination. Both of these organizations meet in 1931, and it is hoped that some definite progress can be made toward the solution of the problem.

As a basis for action, an international Advisory Committee on Electricity, meeting in June, 1930, has prepared recommendations which may be summarized briefly as follows:

1. As a *primary standard of light* a black-body radiator is definitely recommended; other laboratories are asked to consider the specific form of standard which has been developed by the Bureau of Standards, and to make determinations on that form or on others which will be comparable with it.
2. As a *unit* for general use the present international candle is to be retained.
3. Present discrepancies between basic units at carbon-filament color as maintained in the different national laboratories are to be reconciled by comparisons now in progress, and thereafter periodic comparisons and necessary adjustments are to be made under the auspices of the International Committee on Weights and Measures.
4. Through comparisons of colored filters now under way between the national laboratories it is hoped that agreement can be reached on a standard method for measuring lights of various colors. This method can then be used in setting up practical standards for lamps of various types, all based upon the primary standard and all consistent with each other.

Architects and Lighting

During the past year the Illuminating Engineering Society has given great attention to securing better cooperation between the architects and illuminating engineers. As one approach to this problem, three very well attended schools on architectural problems have been held, one at Columbia University, one at Chicago, and one at the Massachusetts Institute of Technology. Such schools for illuminating engineers serve to acquaint them with architects' viewpoints and nomenclature, thus helping to bridge the gap between the two professions. On the part of practising architects greater attention than ever before has been given to coordinating lighting with building design.

Important steps have been taken in fostering better lighting in the homes and schools of the United States. In this manner the best principles of lighting have been made available to school boards and home owners. This work is spreading rapidly.

A code of principles of Street Lighting has been prepared by the Street Lighting Committee of the Illuminating Engineering Society, which is likely to take a very important part in guiding the practise in this field. For the first time experts and engineers representing diverse interests and viewpoints have been able to agree upon a statement of some of the fundamental factors involved.

The Lamp Committee of the National Electric Light Association presents each year to that association a report in which the statistics relating to incandescent lamp production are analyzed in detail, and in which important developments in the production and application of light are reviewed. Those who wish more detailed statistics, as well as those who are concerned with the commercial and engineering problems of lighting, will find valuable the reports of various committees of the National Electric Light Association and the Illuminating Engineering Society.

The Committee wishes to record its appreciation for the assistance rendered in the preparation of this report by Dr. E. C. Crittenden (who contributed the section on the Present Status of Candlepower Standards), Mr. A. L. Powell, and Mr. A. B. Oday.

Applications to Mining Work

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO MINING WORK*

THERE has been a minimum of new installations made this year owing to the general depression.

Hoists. Probably fewer hoists have been installed than in many past years. It is interesting to note that two manufacturing companies alone report that combined they have sold to date nearly 800 induction motor hoists from 200 to 1,800 hp. in size, and over 100 variable control d-c. hoists from 200 to 5,000 hp., the latter two motors in series.

Cleaning Plants. There is a continued trend toward larger and more complete preparation plants especially at mines using mechanical loading instead of hand loading. One plant, Hazle Brook Coal Co., has installed two 200-hp. Westinghouse synchronous motor drives.

Shovels. Electrification of 4- to 10-yard shovels has continued in the metal mines.

Mining Machines. The manufacturers of this specialized electrically driven equipment have been very active in producing new types of mobile high-powered machines. These machines now undercut from 600 to 1,200 tons per day in contrast with older types which did well to undercut 200 tons per day. See Fig. 1.

Loading Machines. Rapid increase of the amount of coal mechanically loaded indicates that these labor saving devices are permanently established in the industry. Various makes have sustained records of 350 to 500 tons loaded per 8 hours. Probably there are 500 such machines now in operation.

Welding. In addition to miscellaneous repair work by electric arc welding several companies have installed full automatic welding heads to be used for filling up the worn tread of locomotive tires and wheels. This has been quite successful and undoubtedly will be very generally used.

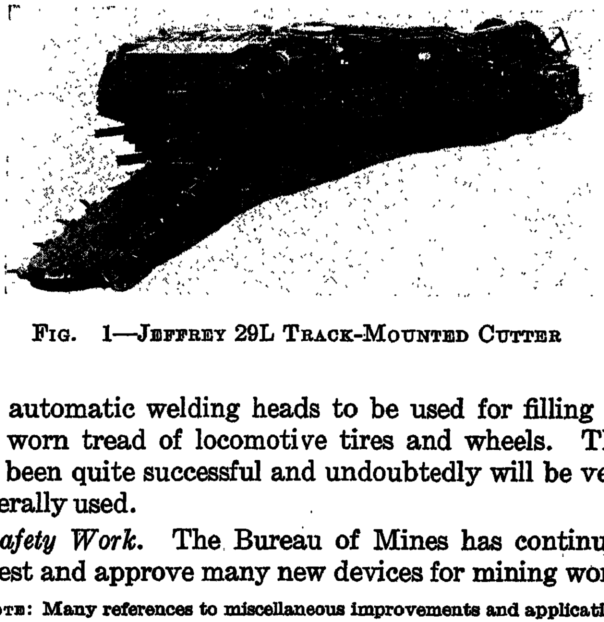

FIG. 1—JEFFREY 29L TRACK-MOUNTED CUTTER

Safety Work. The Bureau of Mines has continued to test and approve many new devices for mining work.

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*COMMITTEE ON APPLICATIONS TO MINING WORK:

O. Lee, Chairman,
A. R. Anderson,
G. Bright,
J. H. Edwards,
F. E. Fisher,
E. J. Gealy,
L. O. Ilsley,
J. E. Kearns,
W. H. Lesser,
D. E. Renshaw,
F. L. Stone,
W. F. Schwedes,
B. F. Tillson,
J. F. Wiggert.

NOTE: Many references to miscellaneous improvements and applications are given in the *Coal Age*, Vol. 36, No. 2, Feb. 1931, p. 76.

Applications to Marine Work

ANNUAL REPORT OF COMMITTEE ON MARINE WORK*

THE major items of activity of the committee for the current term have been:

a. Reprinting Standards No. 45—Recommended Practise for Electrical Installations on Shipboard.

b. Promoting licensing of the electrical operating personnel on shipboard.

c. Keeping in touch with electric propulsion of ships and the electrification of auxiliaries on shipboard.

STANDARDS NO. 45

During the last term of this committee these standards were completely revised to incorporate developments and expansion in the marine practise since the previous issue of June 1927. They were carefully edited and reprinted in October 1930 and are being rapidly sold to all departments of the marine industry interested in electrical work. These standards are recognized and accepted by the various marine classification and insurance societies, naval architects, marine engineers, shipbuilders, and ship owners and are being incorporated in many of the specifications regulating the construction and repair of ships. The increasing use of them testifies to the need of such rules in order to standardize the electrical installations on shipboard and to stimulate the use and proper care of electrical machinery in the marine field.

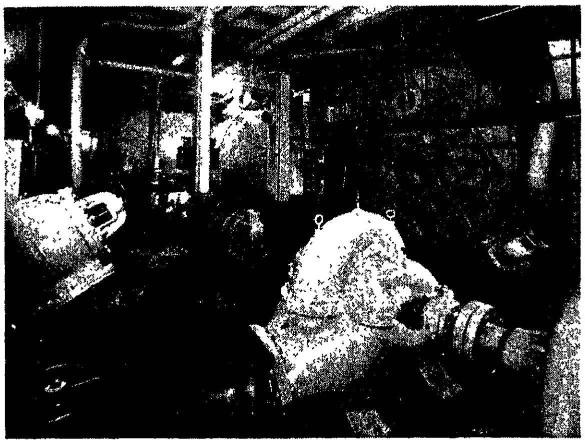

FIG. 1—VIEW IN LOWER ENGINE ROOM, *S. S. Morro Castle*

Propulsion motor in background

They are referred to in the various rules of classification societies not as a requirement but as representing good practise. This regard for these rules is justly merited due to the many years of hard work by experienced representatives of the diversified interests composing the marine field.

The fire alarm rules in the present Steamboat Inspection Service are consistent with the Standards No. 45 and were referred to this committee during their preparation.

OPERATING PERSONNEL

Our efforts were continued with the Steamboat Inspection Service to obtain classification and rating for electrical operating engineers on shipboard.

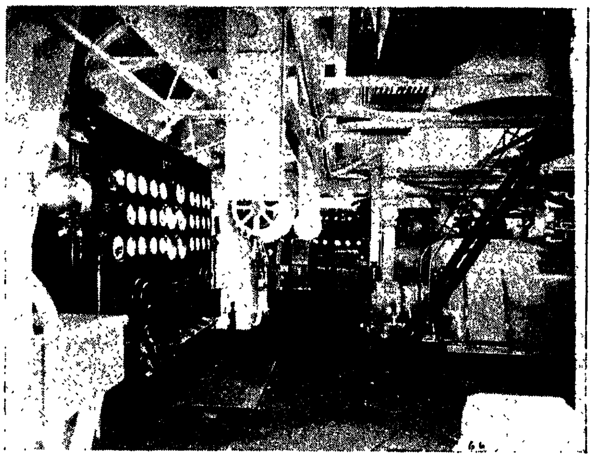

FIG. 2—VIEW IN UPPER ENGINE ROOM, *S. S. Morro Castle*

Propulsion control at left and generators at right

A review of the work of the subcommittee in charge of this item carries one back to the year 1922 when overtures were made to the Steamboat Inspection Service to require the operating personnel on vessels with electric plants to qualify and obtain electrical licenses.

The committee's efforts to date have been rewarded by a slight raising in the standard of the electrical

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*COMMITTEE ON MARINE WORK:

R. A. Beekman, Chairman,
E. C. Alger,
H. C. Coleman,
E. M. Glasgow,
H. F. Harvey,
C. J. Henschel,
Wm. Hetherington, Jr.,
H. L. Hibbard,
J. E. Kearns,
A. Kennedy, Jr.,
J. B. Lunsford,
I. H. Osborne,
G. A. Pierce,
W. H. Reed,
E. P. Slack,
H. M. Southgate
W. E. Thau,
J. Van der Dussen,
A. E. Waller,
O. A. Wilde,
J. L. Wilson,
R. L. Witham,
W. N. Zippler,

questions in the examination for license for steam and combustion engineers.

The Board of Supervising Inspectors has been very courteous and granted a number of hearings. The necessity for the requested action, is recognized by a few of the supervising inspectors and it is hoped that there will soon be a sufficient number to put the movement into effect.

The cause for this movement was the improper maintenance of electrical equipment on shipboard and is today perhaps more prominent than when the movement was started owing to the increase in the use of electrical apparatus and auxiliaries, with the exception of vessels equipped with electric propulsion and all of these are not immune.

On electrically propelled vessels the standard of the electrical force is somewhat higher than on other vessels. Consequently, the electrical apparatus and auxiliaries receive the benefit of more expert attention.

The committee has been in touch with the President of the American Steamship Owners Association soliciting its good offices. Our committee was cordially received and has been requested to submit its proposal relative to the absence of knowledge and training on the part of the operating personnel. This proposal is almost complete and it is hoped it will be submitted at an early date.

The subcommittee is keeping in close touch with this situation and is optimistic in feeling that favorable action will be taken by the Steamboat Inspection Service before long and their regulations modified accordingly.

ELECTRIC PROPULSION AND ELECTRIC AUXILIARIES

The year 1930 takes its place in marine history of the United States with a record of activity, progress, and accomplishment in shipbuilding and marine engineering, which has not been approached since the busy days of the World War. This is, of course, due largely to the stimulation resulting from the Jones-White Merchant Marine act of 1928, which has made available to American ship operators, large mail contracts and loans at low interest rates for construction of new vessels. Thus, our merchant marine is to receive a much needed strengthening by the addition of a fleet of fine ships now under construction or in process of design.

In the design of these last words in naval architecture, electricity has taken an outstanding place. Some will be propelled by means of electricity. All will have electrically driven auxiliaries which are so necessary to the operation of the ship. Electrical appliances will add to the comfort and convenience of the passengers.

In order to illustrate the progress of electric propulsion especially during the past year the following data covering vessels completed or contracted for to January 1, 1931, are listed below.

	Hp.	No. vessels
Total turbine electric in U. S. A.	867,600	62
Total turbine electric outside U. S. A.	127,900	9
Total	995,500	71
Commissioned or under construction during 1930 in U. S. A.	196,900	20
Total diesel electric in U. S. A.	88,280	121
Total diesel electric outside U. S. A.	16,700	8
Total	104,980	129
Commissioned or under construction during 1930 in U. S. A.	15,195	25

It may be interesting to know the individual vessels and their horsepowers involved in the above figures.

Name		Horsepower
Turbine Electric Drive—Ships Commissioned During 1930 in U. S. A.		
Santa Clara		12,600
Morro Castle		16,000
Oriente		16,000
City of Flint (Great Lakes Car Ferry)		7,200
Corsair		6,000
4—Coast Guard Cutters		12,880
2—River towboats		4,000
Total		74,680
Turbine Electric Drive Equipments—Under Construction During 1930		
President Hoover		26,500
President Coolidge		26,500
United Fruit Co.—6 ships 11,000 hp. each		66,000
One Coast Guard Cutter		3,220
Total		122,220
Diesel Electric Drive—Installed During 1930		
Frying Pan	Lightship	350
Fenwick Island	Lightship	350
Nantucket	Lightship	350
Tidewater	Tanker	1,000
Ward Island	Ferry	400
Tenkenas	Ferry	400
Veedol No. 2	Tanker	1,000
L. T. C. No. 1	Tanker	500
L. T. C. No. 2	Tanker	500
L. T. C. No. 3	Tanker	500
Liston	Survey Boat	350
Scott	Towboat	150
Ft. Armstrong	Towboat	150
Cleveland	Tug	800
Rochester	Tug	800
Scranton	Tug	800
Oleon	Tug	800
Venus	Tug	515
Luna	Tug	515
Prescottont	Tug	800
One tug *Vandyke No. 4.*		425
Total		11,455
Diesel Electric Drive—Under Construction		
One yacht		660
One tanker		200
One fireboat		2,130
One ferryboat		750
Total		3,740

Prior to the commissioning of the *S. S. California* in 1928 the total turbine-electric horsepower installed on merchant ships was but 38,800. Out of a total of 356,200 horsepower completed and in course of construction as of the end of 1930, 317,400 horsepower, or

89 per cent, was undertaken during the past three years.

Slightly apart from the marine field, but with equal interest to it, was the installation of a central station in the *Jacona,* which is to be used as a mobile and subsidiary power plant along the shores of the New England Coast. Two turbine generators were installed, each rated 10,000 kilowatts for delivering power ashore at 6,600 volts or 11,400 volts three-phase 60 cycles.

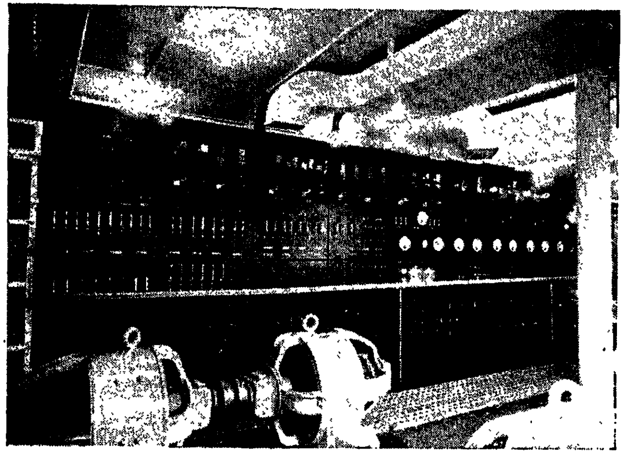

FIG. 3—AUXILIARY D-C. SWITCHBOARD, *S. S. Morro Castle*

During 1930, a 96-in. (wheel diameter) gyroscopic stabilizer complete with electrical equipment, was constructed. This unit will be installed in a large yacht. A second unit with 11-ft. diameter wheel, complete with electrical driving motors, control and turbine generator set for power supply, is nearing completion for installation on one of the largest yachts ever built. The casing of this stabilizer will be of welded construction.

During the year 1930 great strides were made in shipboard installations of modern watertight door control systems. This system provides that in the event of collision electric operation of the watertight bulkhead doors is instantly available. The system provides remote control of the watertight doors from the wheel house as well as at the door itself.

It is the intention of this committee to keep Standards No. 45 up to date and assist in any practicable way the various classification societies and other bodies or interests in the marine field in the application of electricity to marine use.

We further are ready to cooperate with the American Marine Standards Committee in establishing electrical marine standards such as watertight receptacles, etc.

Power Generation

ANNUAL REPORT OF COMMITTEE ON POWER GENERATION*

TWO meetings of the entire committee were held during the year, one at the Philadelphia District Meeting on October 14, 1930, and the second at the Winter Convention in New York on January 28, 1931. In addition to the regular survey of immediate developments and problems in the scope of the committee, a continuing organization or method was adopted through which news items on the subject of power generation will be reported for publication in ELECTRICAL ENGINEERING. Each member of the committee was asked to appoint some one of his business associates as a permanent news correspondent to represent his particular affiliation irrespective of membership in the future on the Power Generation Committee.

The subject of interconnection continued to occupy the major attention of the committee, and especially of the Joint Interconnection Subcommittee on which Messrs. F. C. Hanker, F. H. Hollister, and A. E. Silver represented the Power Generation Committee. The formation of this subcommittee composed of members from the Power Generation, Power Transmission and Distribution and Protective Devices Committees, was predicted in last year's report, and the subcommittee has functioned throughout the year under Mr. Hanker's chairmanship not only to the fullest extent, but has also promoted a close working arrangement among the three main committees in dealing with a subject that has many common elements.

The Joint Interconnection Subcommittee has directed the preparation of a second report on "Grounding," which was presented at the Pittsburgh meeting in March 1931 under the title *Present Day Practise in Grounding of Transmission Systems,* and while of technical import to this committee, is also of interest because the original report on *Grounding* was prepared in 1923 by Mr. E. C. Stone now of the Power Generation Committee.

The Interconnection subcommittee has also sponsored a session in this summer's convention, consisting of four papers that treat the subject of interconnection primarily from the viewpoint of geographical, as contrasted to urban territory, interconnection. The introductory paper, prepared by Mr. Alex. E. Bauhan, is a comprehensive summary of the various services rendered by interconnection, and an exposition of the methods of evaluating the economies to be secured. Two papers that illustrate the plans and operating procedures adopted in different regions, are as follows:

> *Interconnection in New England,* by E. W. Dillard and W. R. Bell; *The Pennsylvania-Ohio-West Virginia Interconnection,* by Howard S. Fitch.

The fourth paper, by G. M. Keenan, is on *Load and Frequency Control on Interconnected Systems* and summarizes the methods in use and the experience on the subject that has accumulated in the past two to three years on practically all the major system interconnections in this country.

The committee reviewed during the year and recommended as of great interest on the subject of interconnection other papers as follows:

> *Governor Performance During System Disturbances,* by R. C. Buell, R. J. Caughey, E. M. Hunter, and V. M. Marquis.
>
> *Reestablishing Excitation of a Loaded Alternator in Parallel with Others,* by D. D. Higgins and E. Wild.

Other papers describing the design of modern power plants that have been reviewed by the committee include the following:

> *The Ohio Falls Hydroelectric Station at Louisville, Kentucky,* by R. M. Stanley and E. D. Wood.
>
> *Modern Steam Stations of Duke Power Company,* by Marshall E. Lake.
>
> *Steam Power Development of the Pacific Gas and Electric Company,* by Richard C. Powell.

Two papers with an introductory summary have been initiated and are now in preparation on the subject of steam and electric drives. These papers are being written in collaboration for the purpose of uniform presentation, and are scheduled for one of the fall meetings this year.

Another activity initiated that will result in a symposium during the 1932 Winter Convention, is suggested by the lack of information reported to the committee on the subject of system operation from the viewpoint of economy and reliability in carrying load schedules. There is considerable literature relating to load division among boilers and generating units in single stations, but new problems in load allocation have resulted from the extensive interconnection of systems previously operating as separate units. It is planned to secure a series of papers describing the practise of at least three of the larger operating systems on which steam generation is exclusively employed, and to reserve the subject of combined steam and hydroelectric sources for later discussion.

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*COMMITTEE ON POWER GENERATION:

F. A. Allner, Chairman,
F. A. Annett,
J. R. Baker,
T. J. Bostwick,
J. B. Crane,
H. W. Eales,
N. E. Funk,
D. L. Galusha,
R. B. Gerhardt,
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G. E. Quinan,
F. A. Scheffler,
A. E. Silver,
W. F. Sims,
A. R. Smith,
E. C. Stone,
R. W. Stovel.

The Progress Report which follows, covers the developments of the past two years. Together with a bibliography of the more salient literature on power generation.

RECENT DEVELOPMENTS AND PRESENT STATUS OF POWER GENERATION

Volume and Distribution of Generation

The combination of a two-year drought and the business depression had a marked effect upon the distribution of the total electric generation in the United States between fuel burning and hydroelectric plants. From 1921 and 1928 the average yearly increase in total generation was quite uniform at 11.5 per cent, in fuel generation at 10.9 per cent, and in hydroelectric generation at 12.7 per cent. Applying these average rates to the figures for 1928 there is a calculated deficit at the end of 1930 of 12.1 per cent in total generation, 4.0 per cent in fuel generation, and 32.5 per cent in hydroelectric generation. These figures show that the loss in hydroelectric generation caused by the drought allowed fuel generation almost to hold its normal increase notwithstanding a decrease of 1.5 per cent in total generation in 1930. The total generation in 1930 was 96 billions, of which 34.6 per cent was generated in hydroelectric plants in contrast to 40.4 per cent in 1928.

Generating Plant Building Programs

The added steam generating capacity in the United States in 1929 was secured by about 57 per cent in new plant construction and 43 per cent in additions to existing plants. The total added capacity was nearly 2,250,000 kw. It is interesting to note that in 1930, in spite of the fact that the total electric production for the year was about 1.5 per cent below that of 1929, there was nearly as much steam generating plant capacity added as in 1929, a total of slightly over 2,000,000 kw. This was divided 47 per cent in new plants and 53 per cent in additions to existing plants. Apparently the depression of the past year is to be reflected in the amount of capacity contemplated for 1931 additions, which is about 1,250,000 kw. These additions are mostly in existing plants where the added capacity is 75 per cent of the total, a condition approaching that of 1928, when practically all of the new steam capacity was in additions to existing plants.

Compared to 1928, the number of new hydroelectric plants and the capacity installed in 1929, was strikingly small; the new installations in 1930 were over three times greater than in 1929, but they still were appreciably less than in 1928. The plants now under construction that will be completed in 1931 will total about 50 per cent of the additions to capacity in 1928, while present indications are that the new capacity developed in 1932 will be only a fraction of the 1931 installations. Contrasted to the schedule of immediate construction are the probabilities within the next few years of the super-capacity plants that are being considered on the Columbia, Colorado, and St. Lawrence rivers.

Major Influences in Current Design of Steam-Electric Plants

The fundamental factors influencing the design of modern steam-electric generating plants are about the same as those which dictated design in the past. They are only modified by new and better apparatus now available, such as improved and alloy steels which make possible the use of higher pressures and temperatures, improved fuel burning equipment and furnaces which permit of much higher boiler ratings and greater efficiences, together with numerous other improvements in auxiliary apparatus.

For a number of years the tendency of steam plant investment costs was upward and these increased costs were justified by the considerable improvement in economy. The point has now been reached where improved efficiencies are becoming increasingly difficult to secure, and any increase in capital cost is difficult to justify. It would seem, therefore, that the effort to lower production costs must lie in reductions in capital investment through simplified design, raising the output of the equipment, and increasing the capacity for a given unit of space.

Probably the most attractive feature in a program of simplification is the possibility of reducing the number of boiler units for a given turbo generator output. Reports published within the last year indicate that the modern boiler has a reliability factor practically equal to that of the turbo generator. It would, therefore, seem that spare boiler capacity should be considerably reduced over past practise up to the point where boiler and turbine capacity would be equal. In other words, the boiler and turbine might be considered as one complete unit. This would be particularly practical where there are several units in the same station, in which case a certain degree of flexibility could be secured where a boiler and turbine forming separate units might be out of service, in the one case for boiler inspection or repairs and in the other case for turbine inspection or repairs.

The greater cleanliness in the operation of fuel preparation and feeding apparatus will now permit the installation of turbines, boilers, and fuel equipment in single buildings without the use of the dividing walls which have up to this time been considered necessary. There has been a number of instances where plants have been constructed without these walls and are giving very satisfactory operating results. The omission of dividing walls not only saves the cost of the wall but reduces the amount of building steel and permits of a more compact arrangement of apparatus, thus bringing about a natural reduction in the cubic contents of the building. In certain cases a reduction in operating labor has also been secured.

Outdoor installations of boilers, turbines, and electrical equipment are advocated by some engineers and many attractive studies have been brought forth. To date, however, no large outdoor installations have been projected. While such installations are not in entire favor with operating engineers the reduced investment has made the designs of interest.

In practically all of the older designs there was a great deal of duplication in the piping layouts. Numerous cross connections, loops and sectionalizing valves were used, partly with the idea of protecting against failure of any part of the piping system and partly due to the desire to protect against failure of apparatus used in the feed-water heating cycle. Experience with operation of piping, valves, and equipment has shown that their factor of reliability is, in general, as great as that of the turbines and boilers. The opinion has frequently been expressed that provisions made for cross-connecting and sectionalizing have never been used even though they have been in the plant for a considerable number of years. Simplification of piping design and reduction in number of valves, joints, etc., would reduce both the capital expenditure and the operating cost.

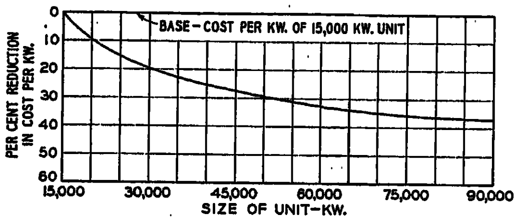

FIG. 1—PER CENT REDUCTION IN UNIT COST OF SINGLE SHAFT TURBO-GENERATOR UNITS DESIGNED FOR 450 LB. 775 DEG. FAHR. STEAM

Considerable thought has been given to reducing the number of duplications of auxiliary equipment, such as condensate, air and circulating pumps for turbo generator units. In designs where several spare boilers were provided it was the practise to install single auxiliaries such as stoker drives, forced and induced draft fans, whereas on the turbo generator units it was customary to duplicate the auxiliary equipment. With the present consideration being given to reduction and possible elimination of spare boilers, the question of duplication of auxiliaries should be carefully considered. The usual argument that it is good insurance to protect the large unit by the installation of duplicate and comparatively cheap auxiliaries, carries some weight. Against this, however, must be balanced the lower capital and operating costs by minimizing the number of pieces of apparatus and simplifying the piping design.

The use of larger units, both boilers and turbines, has resulted in a lower unit cost of equipment and in a marked reduction in the cost of the building per kilowatt of capacity. There is a number of installations either already made or pending, where the capacity of the new turbo-generator unit is from two to three times that of the unit for which the building was originally planned. It is evident, therefore, that the cost of this portion of the building per kilowatt would be reduced to one-half or one-third of the original cost. A few years ago the cost of buildings per kilowatt of capacity was roughly $30. It is, therefore, evident that the possible savings in building alone due to use of larger equipment results in a material reduction in cost per kilowatt. This would have a particular application where equipment is to be installed in a vacant space in an existing building or where it is desired to increase the capacity by replacing equipment in an old plant which is strategically located in the distribution system.

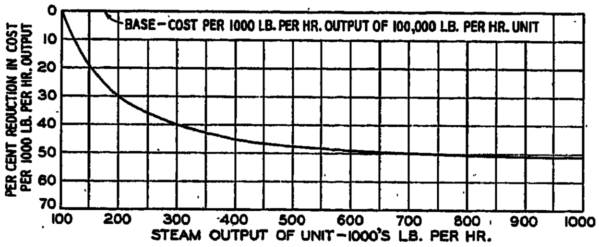

FIG. 2—PER CENT REDUCTION IN COST OF BOILER UNITS DESIGNED FOR 450 LB. 775 DEG. FAHR. STEAM

Prices used in plotting the curve include cost of boiler, superheater, soot blowers, air heater economizer, and pulverized fuel equipment

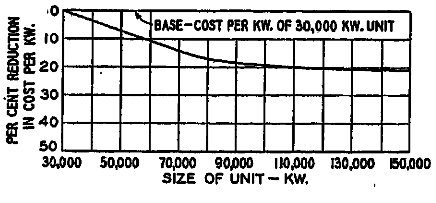

FIG. 3—PER CENT REDUCTION IN COST OF SINGLE SHAFT TURBO-GENERATOR UNITS DESIGNED FOR 1,000 LB. 775 DEG. FAHR. STEAM REHEATED TO 775 DEG. FAHR.

The reduction in floor area has assumed importance not only from the standpoint of building and land value but from the resulting reduction in cost of much of the piping and auxiliary equipment. In order to reduce the floor area some of the modern designs resorted to the vertical compounding of units as typified by the Jersey Central Power and Light Company and the Pacific Gas and Electric Company where a high pressure turbine and generator are mounted on top of a low-pressure generator. By such means and by the increase in the maximum size of turbines from 50,000 kw. in 1920 to 200,000 kw. at present, the floor area has been reduced from an average of 42 sq. ft. per installed kilowatt to less than half that area.

Typical of this trend are the Ford Company in which a 110,000-kw. unit is to be installed where one 12,500-kw. unit is being removed; the Hell Gate Station of The United Electric Light and Power Company where two 160,000-kw. units have been installed in the space designed for two 35,000-kw. units and the Hudson Avenue Station of The Brooklyn Edison Company, Inc., where two 160,000-kw. units have been purchased for the space designed for two 50,000-kw. units.

Along with the increase in size of turbines the weight per kilowatt including the generator has been reduced in the past ten years from about 28 lb. to 15 lb.

The curves in Figs. 1, 2, and 3 will give an indication of the trend toward lower costs with increased size of turbo generators and boilers per unit of capacity. Figs. 1 and 2 represent respectively cost trends for turbo generator and boiler units designed for 450 lb. pressure and 775 deg. fahr. total temperature. Fig. 3 is representative of a compound single-shaft turbo generator where the initial steam condition would be 1,200 kw. and 775 deg. fahr. total temperature, with steam bled at 400 lb. and reheated to the initial temperature.

Along a line totally different from the selection and arrangement of equipment, and also for the purpose of reducing the cost of power generation, has been the cooperative interconnections adopted in the last few years between steam-electric stations and industrial plants. The latter in some cases require large quantities of steam under conditions that may or may not be suitable for the supply of power necessities; in other cases the industrial plants may have the disposal of byproduct fuel either solid or gaseous. It has been found advantageous to both parties in a variety of industries to arrange both electric and steam interconnections whereby power and steam are generated in the most economical fashion, and the fullest benefit derived from diversity in power, steam, and byproduct conditions. In many instances the electric plant supplies both steam and electricity, requiring certain modifications in the standard feed water system. Recent literature has described such arrangements at Deepwater, New Jersey, Rochester, New York, Toledo, Ohio, Baton Rouge, Louisiana, Mobile, Alabama, and Cedar Rapids, Iowa.

Factors at Present Determining Maximum Size of Boilers and Turbines

While large unit size turbo generators reduce the cost per installed kilowatt they sometimes represent a greater capital charge for reserve capacity. A check of available published information regarding peak loads and installed capacity in fourteen large central station systems indicates the following reserve capacity in per cent of the total installed:

Four systems were between 30 and 36 per cent.
Seven systems were between 20 and 30 per cent.
One system was about 17 per cent.
Two were less than 10 per cent.

The same published information indicates that the two systems having the smallest reserve capacity have a substantial percentage of purchased power, so that it is very probable that actual reserve capacity would be materially increased by available spare capacity through interconnection. In one of these systems, where the per cent of reserve capacity is the greatest, it is known that the generator capacity reported on was not all available at the time the tabulation was made, since the boiler capacity in one of the principal plants limited its capacity to a point considerably below the generator name plate ratings. The selection of the very large units in some of the recent developments may have been due to a program of interconnection or expansion which it was estimated would occur within a few years following the installation of the new machine.

Allowance must be made for the loss of the largest unit during operation and also for the possibility of its being out for repairs. If, therefore, units are purchased out of proportion to the size of the system there is likely to result an over-all economic loss. Large units show better performance at comparatively heavy loads. Due to the system reserve requirements it may be necessary to operate at a relatively light load where the economy is poorer. Even the smaller units operating may be affected the same way from the fact of the larger units being on the system. With large units the total amount of auxiliary power requirements for any given system output will also be increased at low system loads. With a large unit carrying heavy load a greater system disturbance would result if the unit should suddenly trip out. Other things being equal the time required for starting a large unit is greater than for one of smaller size.

Transportation difficulties for damaged parts, a longer time necessary for repairs, and larger floor area necessary for dismantling are some of the factors which must be weighed against the lower unit investment and lower labor charges.

Turbine manufacturers have indicated that up to 200,000-kw. capacity in single shaft machines would be feasible. By compounding on multiple shafts the limits, of course, would be considerably higher. One of the limiting features in size would be in connection with the generator and here the use of double windings or raising the voltage will offer a partial solution of the electrical problems.

The limitations to the building of large boilers are more structural than economic. Since at present larger capacity is concentrated in single turbines than in single boilers the problem of boiler reserve is of less importance. Also the experience with pulverized fuel boilers having capacities in the neighborhood of

1,000,000 lb. of steam per hour indicates an availability factor during demand periods approaching 100 per cent.

Large boilers have an exceedingly flat efficiency curve and can be operated at relatively low loads at efficiencies equal to that obtainable from boilers of smaller size. The parts involved in boiler construction are small and do not involve any transportation problems.

Rehabilitation of Existing Steam Plants

Many studies are still being made by steam station designers to increase station capacity by means of improved thermal cycles using higher temperatures and pressures, but not much actual revamping has taken place in the past year or so because of the falling off in power station demand and construction. Then again, while many studies of rehabilitation have been made, all recent improvements in steam station design have been quite broad in their application involving considerable major equipment. Generally speaking, where there has been a demand for increased capacity it has been for such large increments that invariably more consideration is given to the building of new stations with units of large capacity than to some modification of existing generating facilities.

Some steps looking to improved steaming have been taken, such as the installation of water-cooled walls frequently combined with pulverized fuel firing with resultant greater output from the same boiler; also, the installation of air-heaters resulting in a reduction of stack losses. Recent studies made on binary cycles indicate that improvements in efficiency can be made in old plants employing old boilers.

The important recent developments of interest to steam station designers both in the United States and abroad which will, no doubt, in the future have a great influence on rehabilitation, have been:

a. The installation of a 10,000-kw. mercury turbine in the South Meadow Station, Hartford, Connecticut.

b. The installation of high-pressure steam (750 lb.-2,800 lb.) units at Langerbrugge Power Station in Belgium.

c. The construction of new peak load plants in Germany of low pressures.

d. The construction of heat storage plants in Germany.

Rather than follow these lines of securing an increase in capacity and improvements of economy by changes in old stations, the trend in American practise is, with a few exceptions, more along the lines of building new efficient high-pressure steam plants and utilizing interconnections to a greater degree for permitting the operation of the new stations at high capacity factors on base load, and retaining the older less efficient stations for peak loads. With ample interconnections, addition of new capacity at old load centers is not often thought to be as economically advantageous, everything considered, as establishing new generating points where ample land, rail, and water facilities are available.

Reduction in Operating Costs of Steam-Electric Plants

The production of electricity from steam central stations has developed so remarkably in the last decade that it seems fitting in this report to review the progress that has been made during this time.

The average unit production cost has decreased about 50 per cent. The heat consumption per kilowatt hour has been reduced from about 30,000 B. t. u. in 1920 with a best record of 18,000, to an average of 18,500 B. t. u. in 1930 with the best record approximating 12,500 B. t. u. This is for stations using steam only. The mercury steam cycle installation at the South Meadow Station of the Hartford Electric Light and Power Company reports an average heat consumption of around 10,500 B. t. u. per kw-hr.

The progressive increase in the size of turbo generator and boiler units together with the improvements that have resulted in the reduction of supervisory requirements have brought about a constant decrease in labor costs. Great improvement has been made in control equipment with the consequent extension of the scope of supervision of individual operators.

Boiler maintenance costs have been reduced by the use of cooled furnace walls and from the studies by engineers of the effect of operating conditions on maintenance, with a consequent increase in availability of equipment.

Allocation of the load to various stations of a system on a basis which gives a minimum combined cost for each momentary change in load demand and at the same time taking into consideration the effect of loading on the maintenance of equipment, losses incidental to starting and labor costs, has brought about a great reduction in operating costs.

For example, for any particular load demand on the system there is one combination of units and loads at the various stations which will give the lowest combined cost for the system. The determination of this equipment set-up is made by grouping various combinations of units at the different stations through the use of cost input-load output and incremental cost characteristics of the units.

These cost input-load output and incremental cost characteristics are computed from tests on the equipment and it is very important that these tests be obtained with a high degree of accuracy. An operating factor based on a knowledge of the performance of the unit under normal conditions of operation is applied in order to obtain the true normal operating characteristic of the unit. The amount of equipment and location of equipment operating at the various stations must in all cases conform to the standard system operation reliability, which takes into consideration such factors as physical layout, storms, voltage regulation, and protection of the load.

With the determination of the amount of equipment operating at the various stations any change in system demand will be made on the basis of the station incremental cost curves for the equipment operating to a point at which it becomes more economical to operate on another set-up. This method of loading for every momentary change in demand gives a minimum cost for all ranges of load, limits the number of units operating to those required for economy and reliability, and results in a greater utilization of the more efficient units.

In the case of one large power system during the last year the generating capacity of the system was increased about 2 per cent whereas the output delivered by the newer units was raised 13 per cent. As a matter of fact on that system during the year 1930 considerably more kilowatt hours were generated than in 1929 at a total production cost lower than that of 1929.

Table I shows the actual operating results obtained from several different types of stations. The low heat rate obtained by Station A indicates the possibility of a greater adoption of the mercury steam turbine in the near future.

TABLE I—RECENT OPERATING RESULTS

Station	Pressure lb./sq. in.	Temperature deg. fahr.	Cycle	Load factor per cent	Period	Heat rate B. t. u./net kw-hr.
A	70	884	Mercury		Dec.-Feb. 1930	10,180
B	1200 350	750	Reheat regenerative	72.9	Oct. 1930	13,910
C	600	725	Reheat regenerative	65.5	Dec. 1929	12,455
D	1250	750	Reheat regenerative	52.0	Oct. 1930	14,091
E	600	725	Reheat regenerative	71.5	Oct. 1930	14,581
F	600	730	Reheat regenerative	62.7	Feb. 1930	13,368
G	400 250	725	Regenerative	54.8	Oct. 1930	16,290
H	400	700	Regenerative	59.3	Oct. 1930	15,712

Technical Developments in Steam-Electric Plant Design

The seven high-pressure stations described in the last report have been in operation long enough to confirm the results expected from them. Excepting continuing trouble with boiler feed pumps in some of the plants, no unsolved difficulties have been encountered. The more prominent additions to the list of high-pressure plants within the past two years have been the State Line plant near Chicago, the River Rouge plant of the Ford Motor Company in Detroit, and the Port Washington plant of the Milwaukee Railway and Light Company.

State Line plant, described in previous reports, was placed in operation in 1929 with a single three-element turbo-generator unit of 208,000-kw. capacity. The initial steam conditions were 630-lb. pressure and 730 deg. fahr. The extension to the plant now under construction includes two single shaft units of 150,000- and 125,000-kw. capacity respectively. The steam conditions will be 1,200 lb. and 825 deg. fahr., using boilers fired with pulverized coal from unit type mills. An interesting feature in connection with the turbines will be the reheating of steam from the high-pressure cylinder to 825 deg. fahr. at 400 lb. pressure, and its reintroduction into the high-pressure cylinder for expansion to the cross-over pressure of 15 lb. absolute. Reheating will be done in boilers of the reheat type.

River Rouge plant starts operation this year of the very interesting steeple compound 110,000-kw. turbo generator. The initial steam condition is 1,200 lb. at 750 deg. fahr. Live steam reheaters will raise the temperature of exhaust steam from the high-pressure element to 550 deg. fahr. at 80 lb. absolute pressure before it enters the low pressure element. Of particular interest is the fact that this new machine is installed in space originally occupied by two 12,500-kw. turbines and sufficient space will remain for the addition of a second 110,000-kw. unit of the same type at a later date. Two boilers, each having a maximum steam capacity of 700,000 lb. per hour, will serve this turbine.

The Port Washington plant will have one boiler of 690,000 lb. of steam per hr. to operate at 1,300 lb. pressure and initial and reheat steam temperatures of 825 deg. fahr.

In the realm of boilers for pressures above 1,400 lb. there has been no development except in that of size. The Benson and Loeffler boilers are now being built in Europe in capacities above 100,000 lb. of steam per hour; three Loeffler boilers, each with a designed output of 150,000 lb. of steam per hour at 1,850-lb. pressure and 932 deg. fahr. have recently been ordered for a plant in Czechoslovakia. The Benson boiler in use at the Langerbrugge plant in Belgium produces 220,000 lb. of steam per hour at 2,270-lb. pressure. An experimental boiler to operate at 3,200 lb. pressure, being installed at Purdue University, will be the first at that pressure in America. Boilers for 1,800 lb. pressure to supply steam to two 6,400-hp. triple expansion engines are now in course of erection at the Philip Carey plant in Cincinnati. The design of European types of high-pressure boilers was reviewed in the 1929 report.

There is some evidence that the average steam temperature in large power plants in this country has increased slightly during the past two years, and the maximum temperature in use is now considered to be approaching 800 deg. fahr. The Langerbrugge plant in Belgium has operated at a temperature of 850 deg. fahr., for 4½ years and in general there is more of a tendency to use extremely high temperatures in Europe than in this country. In certain respects modern European boiler designs lend themselves to the generation of high temperature steam, and the practise of multi-barrel turbines, common in Europe, is also adaptable to its use. In the United States the Detroit Edison Company has recently put into operation a 10,000-kw. turbo generator at its Delray No. 3 plant, designed to use steam at 1,000 deg. fahr. At the present time the turbine is operating on steam from the station main under 400 lb. pressure and at 750 deg. fahr. For high temperature operation the supply steam will be passed through a separately fired superheater using oil for fuel. The steam main between the superheater and turbine is provided with several types of pipe joints, and other arrangements have been made to note the effect of the high temperature upon the piping, turbine, and superheater, so that the installation constitutes in reality a full scale experimental investigation.

During the past two years the mercury vapor boiler and 10,000-kw. turbine installation of the Hartford Electric Light Company has been perfected to the point where it was available for 82.3 per cent of a period covering 7,520 hours. Excluding causes arising from the use of mercury, the installation would have been available 95.1 per cent of the time. The average thermal rate was 10,310 B. t. u. per net kw-hr. Of the total energy generated, 42.5 per cent was produced by the mercury turbo generator, and the remainder by the steam formed in the mercury condenser.

As a result of the experience at Hartford, mercury vapor units of 20,000-kw. capacity each are being planned for the Kearney plant of the Public Service Corporation of New Jersey and for the power plant of the General Electric Company at Schenectady. The latter installation and an associated steam boiler will be one of the first outdoor steam plants. The mercury vapor pressure will be increased to 125 lb. per sq. in. in these new units, and it is expected that a thermal rate of 8,800 B. t. u. per net kw-hr. will be secured at a load of 20,000 kilowatts on the mercury turbine and with the power developed from the 240,000 lb. of steam per hr. produced at 400 lb. pressure in the mercury condenser.

Higher steam pressures and investigations of troubles resulting from caustic embrittlement have indicated the desirability of boiler drums without seams. Forged drums have been used exclusively for the 1,400-lb. boilers, and lately hammer-welded drums for medium pressure boilers such as the four drum boilers in the James H. Reed Station of the Duquesne Light Company in Pittsburgh, that operate at 400 lb. pressure. The possibilities of fusion welded boiler drums have been studied intensively in the past two years, and "Proposed Specifications for Fusion Welding of Drums or Shells of Power Boilers" were published in the March 1931 issue of *Mechanical Engineering*. The Boiler Construction Code does not at present permit fusion welding of parts where the safety of the structure is dependent upon the strength of the weld.

While no boiler installations have been made of larger capacity than those in the East River and Hell Gate plants in New York that were described in the last report, operating experience at the East River plant has shown that loads can be carried on the boilers there considerably in excess of the expected capacity. A unit generation of 1,250,000 lb. of steam per hour has been maintained, the actual operating limit being met in the capacity of the steam piping leading from the boiler unit. A boiler of 1,000,000 lb. per hr. capacity was recently installed in the Kips Bay plant of the New York Steam Corporation on a floor area originally allotted in 1926 for a boiler of half the output. These large boilers are in reality twin-set boilers having two independent water circulating systems and steam uptake connections, located over a common furnace. The largest single boiler to date has a capacity of about 600,000 lb. of steam per hour.

The installation of boilers of large capacity has focused the attention of operating and designing engineers upon the problem of boiler availability. Although in most plants the number of boilers still exceeds the number of turbo generators, boiler outage in many cases impairs to some extent a plant's generating capacity. Protection of the furnace walls with water cooling surface, improved reliability of the coal feeding and burning equipment, as well as of the ash handling apparatus, increased attention to the details of the auxiliary apparatus, and correct boiler water conditions, have resulted in numerous instances of boiler availability equal to that of turbo generators. The first statistical study of this subject on a large scale was directed in 1929 and 1930 by Mr. C. F. Hirshfeld of this Committee, and was published in *Transactions*, A. S. M. E., Vol. 52, No. 27, p. 265. The data compiled covered only a year and there were several other reasons why the statistics were necessarily inconclusive, but they seemed to indicate that the details of design and construction and operating skill are more important in obtaining high boiler availability than such matters as rate of output per unit of surface, type of fuel, and method of firing. The average availability factor appeared to be between 84 and 90 per cent.

During the period being reviewed, the point of major technical interest in connection with the pulverized coal method of combustion has been the long-time comparisons in the same plant of the unit and bin systems. No generally accepted opinion regarding their merits has been reached. Both systems were installed in the Deepwater plant, New Jersey, where it has been reported that the unit method of firing gave a higher efficiency but a lower reliability. Other comparative studies have been recently published for central stations in Chicago and St. Louis.

Experimentation has continued with the slag tap type of furnace for pulverized coal firing, and its use has been extended. The major difficulty has been the gradual expansion in a horizontal pl
floor, with consequent bulging of t
This results from penetration of the
molten slag, through cracks formed
is cooled during boiler shutdowns.

The size and total fuel burning ca

stokers continue to increase, and steam outputs per boiler of 500,000 lb. per hr. are now possible with stoker firing. There has been only a foot increase in the maximum width of stokers in the last ten years, but the length has been increased from about 13 ft. to 26 ft. 7 in. The largest underfeed stoker in this country is now being installed in the Hudson Avenue plant of the Brooklyn Edison Company, and will be 26 ft. 7 in. long by 26 ft. wide, with a grate area of 694 sq. ft. Stokers of this size have been made possible by extensive cooling of the furnace walls by water cooled surface, improved coal feeding and distributing mechanism, and better control of the air distribution to the several parts of the grate surface and ash pit. In come cases automatic control of the air distribution has been installed. Rotary ash dischargers are almost standard for the larger size of stokers.

Although the fuel burning capacity of stokers per foot of width has been greatly increased, there has been no increase in the rate of combustion per square foot of total grate surface, which is limited by the possibility of clinkering and the blowing of coal from the firebed. Neither has there been any modification of the fact that the combustion rate depends upon the type or burning characteristics of the coal burned. Maximum rates of 60 to 70 lb. per sq. ft. for 10 hour periods have been maintained with good quality eastern coals; 50 to 60 lb. with coals from the central field. Slack coal reduces the maximum rate to the neighborhood of 40 lb. per sq. ft. With all coals an increase in the combustion rate results in an increased loss from incomplete combustion, cinders, soot, ash pit, radiation and unaccounted for losses, in some reported tests these losses reaching a value of 20 per cent.

The limiting temperature for preheated air with underfeed stokers seems to be in the neighborhood of 350 to 400 deg. fahr. Although some installations have attempted to use higher temperatures, it has been found that the stoker maintenance has been adversely affected.

The installation of large turbo generators has continued although no units have been projected larger than those mentioned in the last report. The largest machines now on order are two 160,000-kw. units for the Hudson Avenue plant of the Brooklyn Edison Company. It is noteworthy that all of the turbo generators except one, that are now on order in sizes greater than 100,000 kilowatts, are of the tandem compound type. The exception is the 110,000-kw. high-pressure vertical-compound machine for the Ford Motor Company. The development of generators of large capacity was an essential to the use of tandem-compound turbines.

The record in capacity for single cylinder turbines operating at 1,800 rev. per min. is now carried by two 80,000-kw. turbo generators in the Charles R. Huntley station of the Buffalo General Electric Company. Steam supply to these units is at 435 lb. and 750 deg. fahr.

In the field of high-speed turbo generators, single cylinder condensing units are now in operation in the United States up to 10,000-kw. at 3,600 r. p. m., and tandem-compound units at the same speed up to 15,000 kw. A 15,000-kw. single-cylinder condensing unit of English manufacture has recently been installed in Canada and the C. A. Parsons & Company are willing to build single-cylinder units of 25,000-kw. capacity to operate at 3,600 r. p. m.

Intensive study in turbine design is being made in connection with the use of higher steam temperatures. This problem as well as that of blade erosion is a matter of metallurgy, and the developments to date indicate that it will soon be possible to operate turbines at initial steam pressures above 500 lb. without the necessity of reheating. At the present time a 60,000-kw. unit has been built to use steam at 650 lb. and 825 deg. fahr., and illustrates the simplification and turbine arrangements that will be possible when higher steam temperatures are available.

High-Voltage Generators

There has been a significant demand for generator units of larger and larger capacities, and while this has possibly been the condition since the beginning of power station construction it appears to advance by periods with the most recent one occurring within the past five years. With an increase in generator capacity the designing engineers have been faced with the problem of providing suitable and reliable insulation, conductors, supports, and terminals both internal and external to the machines. Machines of larger capacity for a given voltage mean greater currents. Greater currents mean larger conductors, and consequently greater weights to support normally and greater stresses to provide for at times of short circuits. With the greater currents other external difficulties also arise, such as the provision for the installation of large cables if the power is taken away in underground cables, the reduced carrying capacity of the cables if many are required in restricted spaces, and the provisions necessary to nullify the effect of the sheath voltages. Consequently there has been a very natural trend to higher generator voltage and to multiple-winding machines to reduce the amount of current per conductor.

Unless it is necessary to consider generation at a pre-established voltage and the distribution problems connected therewith, in other words, if generation alone, is to be considered, the most economical voltage usually increases slightly with the increase in the size of the unit. From the generator manufacturer's standpoint, for generators of 100,000 kw. or more, voltages in the neighborhood of 16,000 to 18,000 volts are reported to result in the most economical design. In some instances, economics dictate machines within this range of voltage with transformers for stepping up to the desired transmission voltage, so that, where the generator voltages are not well established, it might be said that for machines above 100,000 kw., the present trend is toward the use of multiple-winding machines with transformers or auto-transformers, rather than to higher voltage machines. The trend will no doubt continue toward multiple-winding machines until the point in capacity is reached when it will prove more economical to increase the voltage.

Some attempts have been made to standardize on generator voltages above 13,800 volts, but since the introduction of successful multiple-winding machines, the study and demand for higher standard voltages has not been so insistent, and may be said to be dormant for the time being. In other words, the double-winding design has made it possible to increase the capacity without increasing the voltage, and to postpone the day when it will be necessary to go to higher voltage. It is not at all unlikely that in the future, generators will be built with more than two windings. The principal difficulty with more than one winding, is in finding sufficient space at the terminals of the machine windings, to install potheads and make connections with satisfactory clearances.

Within the past three years there have been installed in the territory adjacent to Chicago, and there are now in operation, seven 22,000-volt generators with a combined generating capacity of 474,000 kw., ranging in size from 52,500 kw. to 105,000 kw. Additional 22,000-volt generators totaling 432,000 kw., and one 18,000 volt, 115,000-kw. generator are on order for this territory, to be installed during the years 1931-1932.

Outside of the above there have been but four steam-driven generators placed on order or installed recently in this country for voltage ratings above 13,800 volts, namely:

Two 160,000-kw., 16,500-volt units for the Brooklyn Edison Co., and

Two 94,000-kw., 16,500-volt units for the Southern California Edison Company.

Abroad, the outstanding recent high-voltage installations which will be watched with considerable interest are the two 33,000-volt, 25,000-kw., 3,000-r. p. m. generators at Brimsdown, England, and the 36,000-volt, 25,000-kw., 3,000-r. p. m. generator at Langerbrugge, Belgium.

Switch Structures, Switching, and Control

The housing of major switching in both congested and open localities is receiving much study, particularly new installations, because of the advent of metal-clad switchgear. There has been a marked increase in and trend toward the use of metal-clad switchgear in place of indoor cell type and outdoor open type bus structures. Many hundred indoor and outdoor type metal-clad combined switch and bus units of American design are now in service, some with air and some with oil-filled metal enclosed bus compartments.

The first installation in this country, and possibly in the world, of high-voltage outdoor metal-clad switchgear was the 33-kv. substation of the Public Service Company of Northern Illinois, at Wheaton, Illinois. This has been in service since March 1928. Since then there have been many other installations which embody improvements in design and manufacture. This type of switchgear can now be obtained in practically all capacities for which circuit breakers have been developed, including 132 kv. One 132-kv. installation is now being made. The earlier large units involved a considerable amount of field assembly. The latest designs permit complete factory assembly and testing of very large capacity units, such as a full double bus section for one circuit, complete with instrument transformers, buses, etc., for breakers of 22-kv., 3,000-amperes, 2,500,000-kva. interrupting capacity. These units are shipped completely assembled and oil filled thereby entailing a minimum of field assembly and installation work, and avoiding the necessity of drying out, reconditioning, etc., by purchaser.

In the case of several generating stations it has been found that an outdoor oil-filled metal-clad switchgear structure could be installed cheaper than an isolated or separated phase indoor cell structure if the cost of the building is taken into consideration; in some cases a saving as high as 20 per cent has been indicated. Other companies report the reverse where installation conditions are different. One company has proved by actual cost data that for 33-kv. substations the total over-all cost of metal-clad outdoor switchgear erected and ready for service, compares favorably with that of the conventional open type formerly used. This latter comparison, however, would not yet hold for all conditions and localities.

Additional advantages to be gained from complete factory built equipment are the saving in space, the salvage value in case of replacement or rearrangement, and the much greater safeguards to operators and service.

There is a growing demand for faster operation of circuit breakers in case of fault. The manufacturers have made considerable progress toward meeting this condition in the design of circuit breaker operating mechanisms and contacts and methods of extinguishing the arc as well as in the high-speed relay designs. Tests have shown repeated operations where the arcing time was as low as one to two cycles. Large breakers are now available with a conservative over-all time rating of eight cycles. In view of these developments it is quite possible a more severe duty cycle than the 2-OCO may be considered for the rating of oil circuit breakers.

The interest indicated in locating equipment outdoors is not confined entirely to switchgear. There are a few instances where large rotating units have been installed outdoors, and the subject is being given much study.

There has been an increase in the tendency toward the use of steel switchboard panels and the use of hinged panels or cubicals. The desirability of smaller switchboards in the larger power stations and substations is also receiving attention. Various attempts have been made to use miniature equipment, and a smaller number of items, and combination units of instruments and relays. At the same time there is a growing demand for more relays and instruments for one purpose or another. The supervisory system of control seems to be arousing more and more interest as a means of condensing or consolidating the control of a large number of circuits within the convenient reach of a single operator.

The so-called distance relays are becoming more popular. The automatic synchronizing, automatic frequency, and automatic load division control are receiving more attention. Although the first has been available for a number of years, the latter are more recent developments and it is quite possible that the demand for both may grow.

If the predictions indicated in recent announcements with reference to vacuum tube developments, such as the "thyratron," may be anticipated, we are about to see some very wonderful and radical changes in the entire scheme of station control, switching, transformation, transmission and control station design in general. To what extent and how rapidly this may take place is at present problematical. The possibilities we must admit, however, are tremendous. Already there have been some novel commercial applications and very promising laboratory tests extending over a considerable period.

A new type of adjustable-speed control for a-c. motor drive is now available, permitting practically a straight line speed curve with infinitely small steps from zero to maximum. The drive can be installed at nearly the same cost as the drives previously used. The method of control permits high efficiency which in some cases shows a considerable saving over any other type of control. The drive will maintain constant speed regardless of load, is simple, permits the use of standard electrical design features, and to a considerable extent, standard machine parts. To date the service applications have been confined to boiler draft fans and boiler feed pumps, but the drive is adaptable to many other services where fine speed adjustments, and simplicity of operation with high efficiency, are important factors. Thirty-five of these equipments were ordered in 1930, some of which have now been in service for several months. For those who are not familiar with the "Rossman Drive" system it may be of interest to state it consists primarily of an induction motor of standard design, except that the mechanical construction is modified to permit what would be the stator to revolve. This revolving stator is connected by texrope or other means, to a smaller standard d-c. machine fed from a standard motor-generator set or other d-c. source. The speed of the small d-c. machine is controlled by adjusting the voltage impressed on its armature by the generator of the motor-generator set. This may or may not be supplemented by field control. By varying the speed and direction of rotation of the d-c. machine, the load may be driven at any speed within the design range.

Factors at Present Affecting Hydroelectric Development

The increasing attention directed to the large-scale hydro developments on the Colorado and St. Lawrence rivers by governmental agencies is perhaps a new factor influencing the trend of hydroelectric installations. At the same time the federal waterpower licensing policies are being questioned and subject to criticism by both private and political interests, and both have been coincident with severe drought during the past two years in many parts of the country. The complementary value of hydro and steam power sources on systems supplied mainly by hydro has been fully realized, and the principal hydroelectric systems on the Pacific Coast, in the southeastern states, in New England, and in the vicinity of Niagara Falls, have either put into operation during the last two years steam plants of large ultimate capacity or have affected large capacity ties with existing steam plants in adjacent territory. The recent availability of low cost gas and oil fuels in the West, and the advances made in the thermal efficiency of large boilers and turbines, combined with their attractive investment costs, are causing a pronounced predominance there of steam-electric installations that will continue for an unknown period. In the East and South the necessity of steam reserves for low-flow periods has accelerated steam expansion programs. At Niagara the entire water diversion permitted under the existing treaty is utilized and the load growth necessarily must be assumed by steam generation.

Type of Steam Plants on Hydroelectric Systems

A marked similarity in certain design features is noticeable in all of the new steam plants supplementing power systems hitherto dependent upon hydro generation. Gas and oil are the outstanding fuels in the West, while in the East pulverized coal exclusively is fired. Boiler capacities range from 400,000 to 550,000 lb. of steam per hr. at pressures between 425 to 475 lb. per sq. in. with the exception of one plant on the Pacific Coast operating at 1,300 lb. per sq. in. Turbine capacities vary from 40,000 kw. up to 100,000 kw., and one to three boilers are installed per turbine, the usual number being two. The selection of pulverized coal firing appears to be made for reasons other than the emergency starting of boilers; and in fact extra facilities for standby operation of turbines and boilers are provided in only one of the recent plants, which operates on a system where steam generation will be a minimum yet service demands require continuous availability of the steam-electric generator.

General Features of Recent Hydroelectric Development

No hydroelectric plants of unusual total capacities have been put into operation during the past two years, although there have been one or two new records for turbines of large physical dimensions, and the three 49,000-hp. Francis units in the Waterville plant in North Carolina surpass in capacity all previous units of that type operating under high heads. An unusual construction procedure was adopted for the Chute-a-Caron plant on the Saguenay River in Canada. The preliminary drawings for the Boulder Dam plant on the Colorado River reveal no unusual features except the height of the dam and the contemplated power capacity. The Spier Falls plant on the Hudson River is an interesting example of rehabilitation and design investigation by means of model tests. In fact the increasing use of model testing, and its application to the design of the propeller type turbine wheel, constitute the outstanding technical advance in this country in hydroelectric practise during the past two years.

Propeller Turbine Development and Model Testing

Notable installations of propeller turbines of the fixed and manually adjustable blade types were in operation or approaching completion in 1928, and one small capacity wheel of the automatically adjustable type, the Kaplan turbine, was in the course of erection. Since 1928 there have been numerous installations in America of small capacity Kaplan type propeller turbines, that have been designed and installed under European licenses. The Kaplan turbine was first developed in Europe where there are now some large capacity wheels in operation. It is essentially suitable for low-head developments, being used for heads up to about 70 ft. European designs of the fixed blade and Kaplan turbines have been based upon extensive model testing of the turbine wheels as well as of the associated inlet casings and draft tubes.

One of the principal objects of testing models of propeller type wheels has been to determine the limiting conditions of cavitation, for which adjustable draft head conditions are required in the test laboratory. Cavitation, or the formation of bubbles of vapor and air in low-pressure areas adjacent to the runner surfaces, causes a drop of wheel efficiency, but its most prominent effect is the rapid disintegration of the runner material. Cavitation pitting had been encountered in this country with Francis type wheels under certain conditions of specific speed and draft head, and an amount of field experience has been accumulated by which proper operating conditions can be selected for Francis wheel installations. One of the chief advantages of the propeller turbine is the higher specific speed that is possible, but as field data were lacking for such operation, it was considered essential in Europe to determine the optimum installation conditions in advance of construction by means of cavitation testing. Following such investigations propeller turbines of record dimensions, horsepower, and water discharge capacity have recently been installed in the Ryborg-Schworstadt and Kembs plants on the Rhine River in Europe. Pertinent data about these plants are as follows:

Plant	Ryborg-Schworstadt	Kembs
Type of runner	Kaplan	Fixed blade propeller
Number of units	4	5
Head in feet	35	54
Turbine rating-horsepower	35,000	36,000
Water discharge-cu. ft. per sec	10,500	6,800
Rev. per min	75	94
Runner diameter-inches	276	220.8

Cavitation laboratories have been built during the past year, one or two in the United States and one in Canada, for the investigation of design problems concerning propeller type wheels. The construction of a national Federal hydraulic laboratory has also been recently authorized; model testing has been done extensively at one of the technical colleges in the United States for the design of dam spillways, water courses, and turbine settings, and two or three other colleges and individual companies have done a certain amount of such investigation. The first large plant in this country to install automatically adjustable blade propeller turbines is now being built at Safe Harbor on the Susquehanna River in accordance with data obtained from cavitation and wheel setting tests. Six turbines having a rating of 42,500 hp. each at a gross head of 55 ft. are being installed initially. The wheels will have a diameter of 220 in., a water discharge of 8,000 cu. ft. per sec. at rated head and output, and will operate at 109.1 rev. per min.

Briefly described the Kaplan turbine consists of a propeller, or axial flow turbine, whose blade angle is controlled by the speed responsive governor that controls the turbine wicket gates. Separate servo-motors are provided for operating the blades and gates, and a cam is used in the governing mechanism to direct the movement of the runner blades according to the movement or position of the wicket gates. The servo-motor for operating the runner blades forms part of the turbine shaft, and is usually located just under the generator coupling. The links and crank arms for moving the blades are enclosed in the runner hub.

By automatically maintaining the correct relation of blade position to gate opening, the peak efficiencies of a series of propeller wheels each having the proper blade angle for a particular turbine load, are secured, with the result that the efficiency-horsepower curve of such a turbine is quite flat compared to similar curves for fixed blade propeller and Francis turbines, the efficiency at low loads being materially higher. Another feature of the Kaplan turbine is the overload capacity possible by adjustment of the blades, which is of particular value in times of reduced head during high river stages. It is expected that the efficiency of the Safe Harbor turbines will exceed 85 per cent over two-thirds of the load range, and to equal 90 per cent or better for the third quarter of the unit capacity.

Rehabilitation of Hydro Developments

The 57,000-hp. unit recently added to the Spier Falls plant on the Hudson River, New York, exemplifies two distinct tendencies in hydroelectric practise, illustrating in addition to the use of model testing as a design adjunct, the recognition of the value of an over-developed plant for supplying peak-load capacity and the benefit derived from a storage resource by a run-of-river development. At full load the wheel discharge is 7,000 cu. ft. per sec., making it the largest Francis-type runner to date in this respect as well as in physical dimensions. The minimum regulated flow of the Hudson River at Spier Falls is 3,000 sec.-ft., and 5,000 sec.-ft. for 50 per cent of the time. Both the turbine and generator approach record sizes in physical dimensions, the total weight of the rotating element being about 450 tons. The generator stator is 37 ft. in diameter, and the diameter of the scroll-case entrance of the turbine is 26 ft. The unit operates at a speed of 81.8 rev. per min. under a head of 81 ft. Tests of a model of the forebay and intake structures enabled the best forebay outline to be determined with regard to amount of necessary excavation balanced against the head loss in forebay and intakes. The tests revealed that the area of the intake gates could be economically reduced 20 per cent, and this was of special value because the water passages are so large that they gave rise to structural design difficulties. It is reported that the tests resulted in a saving equal to ten times the cost of the tests.

High Head Plants

The Waterville plant of the Carolina Power and Light Company on the Pigeon River in North Carolina has an unusually high operating head, 840 to 750 ft., for a hydro plant in the eastern part of this country. There are three 49,000-hp. reaction wheels in the plant, operating at 400 rev. per min. and these are of record note for their capacity at such a head. The six-mile tunnel from the reservoir created by the dam to the power house is unprecedented even in the notable high head installations on the Pacific Coast. The use of cast steel butterfly valves of 9 ft. diameter under a total head of 840 ft. located in the penstocks near the power house, has been reported quite successful, and is an advance in the size of such valves under high pressure. Johnson valves are also provided in the penstocks where they enter the plant.

The record for large capacity high head Francis wheels will shortly be established in the Diablo plant of the City of Seattle, where two turbines of 90,700-hp. capacity each, to operate under a head of 327 ft. are being installed. The turbines will have cast steel scroll cases and concrete elbow draft tubes.

The record head, however, for Francis wheels occurs in a European plant, the Bringhausen plant in Germany, where four 40,500-hp. horizontal-shaft Francis turbines are being installed to operate under a head of from 950 to 1,000 ft. This is a pumped storage development mentioned later.

Large Scale Hydro Developments

The Beauharnois development on the St. Lawrence River in Canada is notable for the ultimate capacity being planned when the entire flow of the river passes to the power house through the combined navigation and power canal connecting two of the lakes on the flow line of the river. The initial section of the plant will contain ten 50,000-hp. units, to operate under a head of 83 ft. The final capacity will be 2,000,000 horsepower. The construction of the canal between lakes St. Francis and St. Louis, which will be 15 miles in length with a width of 3,000 ft. and a depth of 27 ft. is outstanding because of its magnitude rather than any engineering difficulties.

Another plant that illustrates the scale of development possible on some of the rivers in Canada is the Chute-a-Caron plant on the Saguenay River where four 65,000-hp. units have been installed as the initial step of the future Shipshaw plant of 1,000,000 horsepower. The Chute-a-Caron dam will serve to divert the river for later construction of the Shipshaw plant, but because the head at Chute-a-Caron is only 151 ft. as contrasted to that of 205 ft. at the parallel site, the Chute-a-Caron plant will be operated in the future only during river flows sufficient to supply both plants. The difficulty of construction in the gorge of the Saguenay River is thus being solved by the step-by-step development at the two neighboring plant locations. The river was diverted in a unique manner for the construction of the Chute-a-Caron dam by toppling a concrete cofferdam 92 ft. long into the swiftly flowing current, which caused the flow to pass into an artificial channel previously prepared. The action of the concrete monolith weighing 11,500 tons was accurately predicted by means of model tests.

Storage Developments

The largest hydroelectric plant in New England has been recently completed at Fifteen Mile Falls on the upper reaches of the Connecticut River, in conjunction with the first 220-kv. transmission line in New England. The plant is designed for four 53,000-hp. units at 175-ft. head, and is the first development at two nearby sites which will eventually have a total combined rating of 300,000 horsepower. The completion of the second plant will create a reservoir for regulating the river flow not only for the plants at Fifteen Mile Falls, but also for the plants at Bellows Falls and Vernon, farther down the river. The 220-kv. line carries the output of the plant to a distributing point in the vicinity of Boston.

The Osage plant at Bagnell, Missouri, now approaching completion, will contain six 33,500-hp. units operating under an average head of 90 ft. Without storage this plant would not be feasible since the river flow varies from 324 to 110,000 cu. ft. per sec. with an average of 10,500 sec-ft. The dam will create a reservoir 95 sq. mi. in area having an impounded volume of 87 billion cu. ft., so that the flow of the river will be completely equalized with a draw-down of 30 feet. The average yearly energy available will be about 400 million kw-hr. The Osage plant is also a late example of the omission of a superstructure over the generator bay, the station crane having one gantry leg while the other end of the crane rests on top of the outer wall of the electrical bay which is placed over the penstocks between the dam bulkhead and the generator bay. Low metal housings are provided over the tops of the generators.

The Saluda storage development in South Carolina, described in the last report, was placed in operation last year and is notable for its reservoir capacity of 102 billion cu. ft.

Outdoor Type Plants

The omission of the generator room superstructure continues both for small plants of a single unit and for plants of large installed capacity. Generator designers are predicting that the flexibility of design now possible with fabricated construction, and the latitude permissible in the layout of auxiliary power and excitation systems, will lead to the arrangement of generators to conform to the design of the power house, and that the logical outcome may be the wider use of outdoor generator designs.

Pumped Storage Plants

No installations of pumped storage plants in America have followed the completion of the Rocky River plant in Connecticut, although the use of pumped storage continues popular in Europe where electric system peaks are of shorter duration than in this country. One illustration is the Bringhausen plant on the Weser River in Germany, now under construction, which will contain four combination pump and waterwheel units, each consisting of a 40,500-hp. Francis type horizontal turbine coupled directly to a 36,000-kva. generator, on the other side of which is a clutch for coupling to a 100,000-gal. per min. pump requiring 29,000 hp. for pumping. The plant is connected to an upper reservoir at an elevation 1,000 ft. higher by two penstocks 3,250 ft. in length. The water to be pumped to the reservoir amounts to 26,800,000 cu. ft., from which 500,000 kw-hr. will be generated. Power for pumping during off-peak hours is obtained from interconnected steam plants and other hydro plants on the system.

The horizontal coupling of a pump and a turbine with a generator and/or motor seems to be the preferred arrangement for pumping plants in Europe, and is in contrast to the Rocky River plant layout of pumping units with individual drive motors separate from the main turbine and generator, all of the equipment being of vertical type. The Rocky River pumps which are the largest high-head pumps in this country, have a volute discharge casing without diffusion vanes, and are of the single inlet type. On test the Rocky River pumps showed a maximum efficiency of 91.7 per cent; the efficiency expected by the designers of the German pumps is approximately 80 per cent.

Hydroelectric Generator Developments

There has been a widespread adoption during the past two years of fabricated steel plate construction of both stator and rotor of vertical waterwheel generators, in place of the use of castings formerly standard. Such generator construction of welded steel plate is lighter in weight, is considered to be more reliable mechanically, and is more adaptable to design arrangements. There has been an increased use of the umbrella, or overhung type of generator rotor, in which by means of downwardly curved rotor arms the centerline of the rotor rim or pole faces is brought below the horizontal centerline of the hub. By locating a combined guide and thrust bearing, sometimes of the spherical type, just below the rotor hub, a very material reduction in over-all generator height is secured. The use of rolled steel plates and fabricated construction for the stator has also facilitated the arrangement of ventilating ductwork in connection with the water tube air coolers that are now used very largely for generator cooling. Other advantages of fabricated plate construction are quicker manufacture and possibility of design for shipment without restriction by permissible weights or clearances.

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The subcommittee wishes to express its appreciation of the helpful suggestions received from the main body of the Power Generation Committee.

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†Hydraulic Division.

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Power Transmission and Distribution

ANNUAL REPORT OF COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

THE Committee has continued with its work during the past year through a number of subcommittees organized as in preceding years. All of these subcommittees have been very active in studying the problems in their respective fields, and in promoting investigation work and the preparation of papers for presentation before the Institute. The reports of the work of the several subcommittees follow.

SUBCOMMITTEE ON DISTRIBUTION

One of the most interesting developments in connection with the distribution of electrical energy during the past year has been the practical application of the network principle to primary distribution. The economies and improvements to service which are made possible through the adoption of the low-voltage network have been so clearly demonstrated by the generally satisfactory performance of the many recent installations, that a wider application of the principle is not surprising.

At the present time there is being installed a 4-kv. primary network in Pittsburgh, Pa. This will serve a residential district of comparatively low-load density which was previously served by an overhead radial system.

The application of the network principle to 4-kv. service for such an area requires certain radical departures from the designs which have become fairly well established for distribution. Since underground construction in the areas of low-load density is not usually justifiable from an economic viewpoint, overhead construction must be used. The primary network deserves careful consideration from the standpoint of economy, reliability, and system planning in handling loads in areas not readily adaptable to low-voltage network distribution.

The past year has seen a continued application of vertical network distribution in large office buildings. This type of distribution has been used in a number of large cities including New York, Pittsburgh, and San Francisco. At the present time several features of design have not been settled. These features are being given consideration and it is expected that with the extended application of the vertical network principle a better understanding of them will result.

The question of secondary faults on low-voltage a-c. networks is still being discussed at length. There is a feeling among some engineers that the problem is not radically different from that encountered on the d-c. network. Others feel that short-circuit currents available are generally less and the condition is therefore more difficult. The use of buried cable has also been studied and tests made which will be reported in the near future.

SUBCOMMITTEE ON LIGHTNING AND INSULATORS

Past Year's Activities in Investigation Work

The activities in the field of lightning investigation during the past year have been carried on by means of:

1. Field investigation of natural lightning.
2. Field investigation with artificial lightning.
3. Collection of operating data on lightning performance of lines.
4. Theoretical analysis and coordination with the past lightning data.

In the field investigations, use was made of cathode-ray oscillographs, klydonographs (and surge recorders), surge indicators, lightning intensity recorders, direct-stroke recorders, and artificial lightning generators. This year the field investigation was extended to include a wood-pole line on which was recorded lightning voltages in the order of 5,000,000 volts.

By concentrated efforts in the field with the artificial lightning generator, a vast amount of knowledge has been gained on the effect of tower footing ground resistance, counterpoises, effect of normal voltage in sustaining a power arc in the presence of lightning flashover of a line, and particularly on the operation of the lightning arrester.

The behavior of traveling waves at the junction of cables with overhead lines was further studied by the use of the artificial lightning generator with particular attention to the application of lightning arresters.

Extensive use was made of the lightning (direct) stroke recorder and our knowledge in regard to the

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*COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION:
P. H. Chase, Chairman,
E. T. J. Brandon,
C. I. Burkholder,
A. B. Campbell,
C. V. Christie,
R. N. Conwell,
O. G. C. Dahl,
Harold C. Dean,
L. L. Elden,
H. S. Evans,
R. D. Evans,
F. M. Farmer,
J. H. Foote,
K. A. Hawley,
L. F. Hickernell,
J. P. Jollyman,
A. H. Lawton,
L. L. Perry,
T. F. Peterson,
D. W. Roper,
A. E. Silver,
D. M. Simmons,
C. T. Sinclair,
L. G. Smith,
Philip Sporn,
W. K. Vanderpoel,
C. F. Wagner,
H. S Warren,
T. A. Worcester.

current in direct strokes amplified, and made more definite.

The cathode-ray oscillograph application was modified to trace the history of a natural lightning wave over a period of some 2,000 microseconds, in addition to recording the initial characteristics of the waves.

Surge indicators were used for the first time, although mentioned in last year's report. These definitely established the fact that a lightning flashover of a transmission line can take place without sufficient follow-up current flowing to trip out the line.

The past year has brought out some intensive study of a theoretical nature on the lightning problem dealing with the mechanism of the lightning stroke and the subsequent surges which may appear on a transmission line. Both the direct stroke and induced stroke have been analyzed and the conclusion pointed out that only direct strokes appear to have consequential effect on the highly insulated lines, while medium and lower insulated lines will be affected in an increasing order by induced strokes.

Results of Last Year's Work

It is impossible here to point out in detail all the results of last year's investigation. There are, however, some outstanding accomplishments, among which the following are cited.

1. The effectiveness of ground wires in reducing lightning voltages and line outages has been further demonstrated.
2. The value of low tower footing resistance in lessening the effects of lightning voltages has been shown.
3. Currents in the lightning stroke in the order of from 50,000 amperes and upwards have been indicated.
4. Counterpoises at a tower footing, even although of comparatively short length are beneficial in reducing the lightning voltage to which a line may be subjected.
5. Lightning sparkover of a line can take place without power follow current.
6. Lightning voltages of both direct and induced stroke origin appear to be present on transmission lines. It is not known in what normal insulation and voltage range the induced voltage ceases to be a factor in line flashover.

Insulation Coordination

In order to coordinate insulation on a lightning basis, its lightning characteristics must be known. Whether these are secured on a single impulse wave or voltage time lag basis, a standard test method must be agreed upon by all who supply this type of data. The Committee has this matter well in hand at the present time, with the probability that an agreement will soon be reached by all actively engaged in this work whereby a group of two or more preferred waves will be used for securing this type of data.

Insulator Flashover Values.

It has been known for some time past that discrepancies have existed in 60-cycle flashover values assigned to insulators of practically the same physical dimensions. The cause for these different flashover values has been traced to a variation in humidity conditions at the time and place of test. A great deal of experimental work has been done on this problem, and it is expected the information obtained will soon be made public through a group of papers before the Institute.

SUBCOMMITTEE ON INTERCONNECTION AND STABILITY FACTORS

In order to coordinate the work of the Power Generation Committee, the Protective Devices Committee and the Power Transmission and Distribution Committee in the field of interconnection and system stability, there has been formed a Joint Interconnection Subcommittee. This Subcommittee was organized during the year and has arranged several sessions of interest in the field of transmission and distribution. These include the session on System Grounding at the Pittsburgh Meeting in March 1931 and the session on System Interconnection for the Summer Convention of 1931. In addition, plans are under way for a symposium at the Winter Convention of 1932 on the subject of Machine Characteristics and System Stability. In last year's report mention was made of the organization of a Subject Committee on Definitions of Terms Used in Stability Investigations. The work of this Subject Committee is now substantially complete and it is planned to present it as a paper at the Winter Convention in 1932.

SUBCOMMITTEE ON CABLE DEVELOPMENTS

This year has witnessed the continued practically universal use of shielded cable (type H) for all three-conductor high-voltage cables. Other tendencies are the increased use of oil-filled cables, the use of super-calendered paper, a great increase in the use of non-metallic armored cables for direct burial in the ground for low-voltage work, and the use of steel-wire armored, non-leaded cables for submarine service and for vertical distribution cables in high buildings.

The Following Cable Installations May Be Noted:

1. A second circuit, 175,000 kva. (winter rating), of single-conductor 132-kv. oil-filled cable about 6 miles long by Commonwealth Edison Co. in the same conduit bank as their first circuit. The new circuit has 1,100,000 cir. mils conductors as compared with the 600,000 cir. mils previously used. The larger conductor size is made commercially feasible by insulating sleeves and grounding devices to eliminate sheath losses. Due to the many improvements in accessories and technique, the net result was that the investment cost per kva. of capacity is less than one-half the cost of the first line.

2. Two lines of single-conductor 600,000-cir. mil 132-kv. cables each three-quarters of a mile long installed by the Commonwealth Edison Co. one (90,000 kva. rating) similar to the cable of paragraph 1 above, and the other (95,000 kva. rating) with novel features of oil channels cut in the interior of the lead sheath as well as an oil channel in the conductor, a simple and small stop-joint, making it possible to have every joint a stop-joint, which joint is practically a factory-made and factory-tested joint.

3. The Deepwater installation of the United Gas Improvement Co. across the Delaware River consisting of two 60,000-kva. circuits (and two spare cables) of single-conductor 750,000-cir. mil 75-kv. solid type cable manufactured and installed in single lengths each about 4,000 ft. long. These are the first 75-kv. submarine cables and longest lengths of power cable ever manufactured.

4. Two circuits rated at 55,000 kva. each of single-conductor 750,000-cir. mil 75-kv. solid type submarine cable of the Union Electric Light and Power Co. of St. Louis across the Mississippi. The cables were made and installed in single lengths of about 2,800 ft. each.

5. An installation of five three-conductor 48,000-kva. 66-kv. oil-filled cables by the Union Gas and Electric Co. of Cincinnati. This is the first three-conductor 66-kv. oil-filled cable, and is buried direct in the ground. The conductor size is 500,000 cir. mils sector, insulated with 0.40 in. impregnated paper and shielded. The cables are made in single lengths 1,300 ft. long, thus avoiding joints, and are steel-tape armored cables buried directly in the ground.

6. Three commercial installations have been made during the year of three-conductor 33-kv. to 35-kv. oil-filled cable, although the amounts were rather limited. These installations were made by the city of Los Angeles, the Staten Island Edison Co., and the Syracuse Lighting Co. All three installations were made with three-conductor type H cable with oil channels in the filler spaces. A novel feature was the three-conductor positive stop-joint by the city of Los Angeles, and also the fact that a large installation of cable with oil channels in the filler spaces including a more viscous oil was installed by this company, who after installation replaced the oil in the channels by oil of the type used in oil-filled cables.

7. An experimental installation of single-conductor 132-kv. oil-filled cable by the Commonwealth Edison Co. of Chicago in cooperation with two manufacturers, each of whom supplied 1,000 ft. of 450,000-cir. mil or 500,000-cir. mil cable insulated with 0.40 in. paper and 1,000 ft. with 0.50 in. paper. The purpose of this experiment is to study the limiting stresses and temperatures in oil-filled cable for present and future voltages.

8. An experimental installation of single-conductor 132-kv. cable by the Public Service Electric and Gas Co. as a continuation of their 1927 experiment studying the possibility of "solid type" insulation for 132-kv. service. The installation consists of three cables each of 500,000 cir. mils and 1,000 ft. long, two supplied by one manufacturer and one by another. Each manufacturer supplied a length of solid-type cable. The third cable is of an intermediate or hybrid type, using oil intermediate in viscosity between that of an oil-filled cable and of the usual type of cable, thus greatly facilitating installation methods while sharing in part the operating advantages of an oil-filled cable.

The Subcommittee on Conduit and Manhole Temperature of the N. E. L. A. Underground Systems Committee has standardized on conditions and constants for calculating current-carrying capacity. This standardization has made it possible to calculate current-carrying capacities of cables covering a large range of sizes and conditions. These tables of carrying capacities will be published by the Underground Systems Committee, and should prove of great value to the industry.

SUBCOMMITTEE ON STEEL TRANSMISSION TOWERS AND CONDUCTORS

The Subcommittee on Steel Transmission Towers and Conductors was organized to assist in the standardization of steel transmission towers and conductors by clarifying the problems associated with their design and application, by papers prepared by recognized authorities on these subjects and presented before the Institute.

The work of the Subcommittee has been divided into three groups, each of which is responsible for one of the following subjects:

I—Towers.

II—Clearances and Electrical Characteristics.

III—Conductors.

During the past year, four meetings of the Subcommittee have been held, together with some additional meetings of groups within the Subcommittee.

An addition to the clause of the N. E. L. A. specifications on uplift of tower foundations and a recommendation for a straight line compression formula for the N. E. L. A. specifications is in course of preparation. Consideration is being given to elimination of the term "factor of safety" by substituting therefore "per cent overload." Contact is being maintained with the A. S. T. M. on its investigation of embrittlement of hot dipped, galvanized steel.

It is proposed to recommend that the 60-cycle flashover be the basis for clearance of the tower under winter or heavy loading conditions and that lightning flashover be the limit for summer or light loading conditions. The width of the right-of-way is to be limited by similar conditions.

Intensive study is being given to the vibration of conductors. Efforts are being directed principally to the coordination of experimental work being done by widely separated investigators, including California, Texas, Illinois, Michigan, Ontario, England, and Australia. A bibliography is being established as an adjunct to this work.

The present membership of this committee, including the chairman, is now twenty, with five men in Group I, six men in Group II and eight men in Group III.

It is felt that the work of this subcommittee is now progressing smoothly and during the next year, concrete results can be shown as the result of its activities.

CONCLUSION

For the sake of brevity, this year's report excludes the bibliographies of papers which appeared in last year's report. It is planned to include such bibliographies in the Annual Report at appropriate intervals, rather than every year.

In conclusion, it is desired to stress the conscientious and enthusiastic work of the chairmen and members of the subcommittees to whose liberal contributions of time the progress made is due.

Transportation

ANNUAL REPORT OF THE COMMITTEE ON TRANSPORTATION*

YOUR Committee on Transportation submits a brief review of the recent developments of importance in the application of electricity to transportation.

STEAM RAILROAD ELECTRIFICATION

Pennsylvania Railroad

The Pennsylvania Railroad has been actively continuing its electrification program. On June 29, 1930 electric operation was inaugurated between Philadelphia and Trenton, N. J., a distance of about thirty miles. On July 20th, electric operation was started between Philadelphia and Norristown, Pa., on the Schuylkill Division, seventeen miles. Fifty-nine multiple unit cars have been recently acquired. This installation completes the suburban electrification about Philadelphia. Distribution of power is at 11,000 volts, 25-cycle, single-phase. The equipment for suburban service is at present all motor cars, with multiple unit control.

The new suburban terminal at Broad Street was opened on September 28th. This is of necessity, entirely electrically operated, for the tracks are, like those of the passenger terminal at New York, under cover. The new suburban station at Thirtieth Street on the west bank of the Schuylkill River was also placed in service at this time. This will ultimately be an integral part of the Pennsylvania Terminal at West Philadelphia now under construction.

The Pennsylvania Railroad now has in electrified operation about Philadelphia, 132 miles of route and 437 miles of track; 345 multiple unit cars are in service.

Work is actively progressing in the New York Terminal zone preparatory to changing from the 600-volt third rail to 11,000-volt, single-phase trolley wire between Sunnyside Yard and Manhattan Transfer. This installation, which will among other things allow New Haven locomotives to enter the Manhattan Terminal, should be completed during the present year.

Construction is progressing between New Brunswick and Manhattan Transfer and will shortly be started between New Brunswick and Trenton, and between Wilmington and Washington.

Four types of locomotives are being developed for the complete electrification. Two passenger types, one freight and one yard switching. The light passenger type (designated as 0-1) is of 2-B-2 arrangement, and two of these units will be used on the heavy passenger trains. The heavy passenger type (P-5) is of the 2-C-2 arrangement. The freight type (L-6) is of the 1-D-1 arrangement. The passenger locomotives will use twin motors rated at 500 hp. per armature, or 1,000 hp. per axle. The freight locomotive will be equipped with four motors of single armature type, and will thus have a rated capacity of about 2,000 hp.

Long Island Railroad

The multiple unit suburban service of the Long Island portion of the Pennsylvania Railroad, operated by third rail distribution, is rapidly growing. Eighty-five multiple unit cars now being added to the equipment, bring the total number of cars to 825. To provide power for the increasing load, the Floral Park, substation is being remodeled and will be equipped with two rectifiers of 3,000-kw. capacity. Four new substations—Hempstead, Manhasset, Rockaway Park, and Goose Creek—are being built, in addition to four planned for installation next year. Each of the new substations will contain one 3,000-kw. mercury arc rectifier, except at Goose Creek where portable synchronous converter equipment will be installed. The rectifiers will be adapted for 60 or 25 cycle operation, an external reactance being added for the lower frequency.

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*COMMITTEE ON TRANSPORTATION:

Sidney Withington, Chairman,
P. P. Ash,
R. Beeuwkes,
A. E. Bettis,
J. V. B. Duer,
H. H. Field,
I. W. Fisk,
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W. B. Potter,
R. H. Rice,
A. S. Richey,
S. A. Spalding,
N. W. Storer,
W. M. Vandersluis,
R. H. Wheeler,
R. P. Winton,
G. I. Wright.

Delaware, Lackawanna & Western Railroad

The suburban electrification of the D. L. & W. R. R. was inaugurated between Hoboken and Montclair, N. J. on September 3, 1930, the service to South Orange, N. J. September 22, 1930 and that to Morristown, N. J. December 18th. The present electric installation was completed with the electric operation in January 1931 to Gladstone and Dover, N. J. This electric operation comprises about sixty-eight route miles and one hundred and fifty-eight miles of track; and includes 282 multiple unit cars. These cars operate in pairs, the units consisting of one motor car and one trailer each. Five substations, each containing mercury arc rectifiers, furnish the distribution power at 3,000 volts direct current. Two electric three-power locomotives (oil, storage battery, and trolley operated) have been acquired and are used for switching and transfer service between Jersey City and Secaucus freight yards. The D. L. & W. is the first heavy traction service in this country to utilize 3,000-volt direct current on motor cars, and the first to install exclusively mercury arc rectifiers.

New York Central Railroad

The Cleveland Union Terminal electric operation was inaugurated June 28, 1930. This project comprises 17 miles of route and about 60 miles of track, between Collinwood and Linndale, Ohio, and employs twenty-two locomotives. These locomotives are 2-C + C-2, weighing about 204 tons, of which 150 tons is on drivers. They are designed for a maximum speed of 70 mi. per hr. The locomotives are used interchangeably for switching or road service. Train heating boilers, oil-fired, are provided on the locomotives. The power distribution is by means of 3,000-volt direct current, using a catenary system. This is supplied from two substations, one 3.5 miles west, and the other 7.2 miles east, of the Union Station; each equipped with motor-generators, remotely controlled from the terminal building by a supervisory system of the synchronous selective type. The installed capacity is 9,000 kw and 6,000 kw. respectively.

The New York City electrification of the New York Central is progressing. The "West Side" tracks will be electrified by the middle of the current year as far south as Seventy-second Street, the tracks north of that point being on a viaduct, or on private right-of-way. Forty-two freight locomotives have been purchased for this service. Distribution of power is by direct current at 650 volts using a third rail. South of Seventy-second Street the tracks are on city streets, and the operation will be accomplished by three-power (oil-electric-storage battery) locomotives, of which the railroad has purchased thirty-five.

Reading Railroad

The electrification of the Reading Railroad at Philadelphia is progressing, and operation should be started about the middle of the current year. This project includes about 69 route miles and 161 miles of track; seventy multiple unit cars will be operated initially. The distribution system is at 11,000 volts, single-phase, 25 cycles.

Great Northern Railway

The Great Northern Railway has placed in service four new motor-generator locomotives with axle arrangement 1-C + C-1, essentially similar to those of that type already in operation. Each locomotive weighs 263 tons, of which 210 tons is on drivers. The distribution of power is at 11,000 volts, 25 cycles, single-phase.

Illinois Central

The Illinois Central Railroad placed in service in 1930, four 100-ton straight-electric locomotives for switching service, and also five 600-hp. oil-electric locomotives of the Diesel type. The motive power now in suburban service consists of 280 multiple unit cars, 140 of which are motor cars and 140 are trailers. In the freight switching service, there are now four straight-electric locomotives and six 600-hp. oil-electric. The power distribution is 1,500 volts, direct current. About 154 track miles are electrified.

New York, New Haven and Hartford Railroad

The final extension of the New York, Westchester and Boston Railway to Port Chester, N. Y. was completed late in 1929. The New York, Westchester and Boston—an integral part of the New Haven electric operation, now operates from Harlem River to Mount Vernon, N. Y., with branches to White Plains, N. Y. and to Port Chester, N. Y. The total New Haven a-c. electrified mileage is now about 577 track miles, over approximately 116 miles of route. The road operated, as of the end of 1930, 141 electric locomotives and 267 multiple-unit cars. The New Haven last year placed in service nine multiple-unit cars. During the current year there will be added to the equipment, ten 200-ton passenger locomotives and 33 multiple-unit cars. The power distribution of the New Haven is at 11,000 volts single-phase, 25 cycles, but the passenger motive power is designed to take power also from the New York Central third rail at 650 volts, direct current.

Substations for Electrified Railroads

The conversion of power for distribution on the Delaware, Lackawanna and Western electrification is, as previously noted, entirely by means of mercury arc rectifiers. This installation consists of 18 units in 5 substations with a total capacity of 40,000 kw. The rectifiers are also provided with a means of compounding, so that voltage can be maintained over a fairly wide load range at substations. Reference is made to the report of the Technical Committee on Automatic Stations covering this feature. Four of the substations are manually operated but are provided with many of the usual automatic protective features. One substation is completely automatic. Remote and supervisory control are provided for the automatic substation and the tie stations.

In its electrification the Pennsylvania Railroad has continued with the 11,000-volt distribution system now in use on other parts of its system involving step-down transformer substations installed at intervals of 7 to 8 miles. The Reading electrification consists of the three-wire distribution system with 11,000 volts on the trolley and a feeder of 33,000 volts. Auto transformer stations are used at intervals, to transfer energy from the 33,000-volt feeder to the 11,000-volt trolley. Some of the substations of the Pennsylvania Railroad electrification are remotely controlled from adjacent signal towers, and those of the Reading are controlled by supervisory control so that the power director indirectly or directly has control of all circuit breakers within his jurisdiction.

The Cleveland Union Terminal Substations contain two and three 3,000-kw. motor-generator sets respectively, with complete automatic control. A synchronous selective supervisory control system with remote telemetering provides the dispatcher, located in the Terminal Building, with complete supervision and indication of the substation, feeders and tie station.

High-speed air circuit breakers have been employed in all substations of the d-c. systems mentioned above, and the Pennsylvania Railroad and Reading Railroad a-c. systems have employed high-speed a-c. breakers of the air and oil type. Reference is made to the report of the Committee on Protective Devices for data regarding the various types of high-speed circuit breakers available for a-c. and d-c. service.

Electric Locomotives

A novel development in the field of a-c. locomotive design has occurred abroad. In this design the low-voltage terminals of the transformer are permanently brought out, and all voltage control for the motors is by means of an oil-immersed tap changer and air switches from the high-voltage windings. The arrangement is a development of the growing use of the scheme of "tap-changing under load" and if it is found to be practicable under service conditions, should materially simplify the design of a-c locomotives.

A novel development in electric locomotive design has been accomplished in the new locomotive of the Illinois Central Railroad. This compensates the tendency of reduced weight upon the forward drivers at high drawbar loads, especially at starting, on account of the moment of the drawbar pull and rail reaction. The arrangement consists of shunts for weakening the field of the leading motor of each truck, which reduces the tractive effort of the leading motor and increases that of the rear, in proportion to the field strengths of the two motors. The forward drivers thus show less tendency to slip and the drawbar capacity is therefore increased.

There has been a number of notable improvements recently in the design and construction of the single-phase motor which have materially decreased its weight per horsepower and have improved efficiency and power factor. Attention is called to the report of the Committee on Electrical Machinery for descriptions of these developments.

Oil-Electric Locomotives

In addition to 35 oil-electric-storage battery locomotives acquired by the New York Central Railroad for the "West Side" operation in New York City, seven similar units have been placed in service in Chicago, and as above stated, two on the Delaware, Lackawanna & Western Railroad. The Canadian National last year acquired a Diesel locomotive, as have various industrial concerns.

A novel arrangement of Diesel locomotives has been developed, wherein the engineer's driving position is raised to a sort of mezzanine floor, so the engineer may look over the top of the train he is moving. In this design, controllers, air brake handles, etc., are provided at both sides of the cab so the driver may move from side to side as desired to observe signals from the switching crew.

Rail Cars

Fifty-six rail cars of gasoline and oil electric design were produced in this country during the past year. As an indication of the increasing use of this type of equipment in heavier service, the average power of these cars was about 450 hp. as compared with about 350 hp. the average in 1928.

MARINE TRANSPORTATION

A number of turbo-electric and Diesel-electric vessels of various types was produced in 1930. The *S. S. President Hoover* is the largest electrically driven liner produced thus far. The propelling equipment consists of two 14,000 hp. turbines with three-phase 10,100-kw. generators, and two 13,250-hp. synchronous induction motors. Auxiliary electric apparatus on steam and Diesel propelled craft has developed in a number of different directions, replacing steam auxiliaries. Attention is called to the report of the Technical Committee on Application of Electricity to Marine work.

AVIATION

A number of electrical devices has added to the art of aviation during the past year. Among these is the "turn compensator," an electrically driven device to correct the error experienced in all types of "earth inductor" compasses when the direction of the ship is suddenly changed. This device may also be used as a "turn indicator" to show quickly and with reasonable accuracy the angular change in direction.

Recently developed engine-performance indicators, electrically operated, showing oil-pressure, oil-temperature, speed, etc., are of value especially on multiple-engine ships, by permitting remote indication.

In the field of illumination for aviation, wing-lights set into the leading edge of plane wings increase efficiency by reducing non-productive air resistance. Airways are being illuminated by increasingly powerful and efficient beacons. The illumination of landing fields by means of flood lights and marking lights is keeping pace with other developments.

Railroad Signaling

Centralized traffic control by means of coding systems is rapidly being extended on railroads. This enables a dispatcher or tower operator to remotely control switches and signals over a large territory and thus direct trains quickly and effectively without the necessity of train orders.

Urban Transportation

The chief developments in urban transportation are efforts to obtain faster car acceleration, higher speeds, and better braking, to compete with increasingly difficult traffic conditions. The increased use of double-reduction and worm gears has made the operation of higher speed motors practicable with marked decrease in weight (especially in unsprung weight). Lower floors, with greater speed in loading and unloading, are features of some of the new drives.

The modern trolley bus is being used for many services where street cars or gasoline buses were applied previously. Economy of operation and low investment cost insure a widespread use of trolley buses, especially where it is possible to utilize existing power plant, substation, and power distribution facilities. In Chicago, for instance, over fifty-seven miles of line have been equipped for trolley bus operation, and seventy-five buses are in use.

The gas-electric coach, which has hitherto shown its chief advantages in congested urban traffic where frequent and rapid acceleration is necessary, is invading the interurban field.

Attention is called to the expansion of the subway mileage in Philadelphia, New York, and Brooklyn. Plans for a subway in Chicago have been approved.

Rail Fissure Detector

The Sperry device for detecting fissures in track rails has been operated intensively throughout the country with valuable results. Continued use of this device should materially reduce rail failures.

Welding

Electric welding is increasingly used not only in railroad shops (as in other industries), but for building up rails and "special work" at frogs, crossings, etc. Rail bonds for traction and signal purposes are in many instances welded to the head of the rails.

Vertical Transportation

The ever increasing height of buildings necessitates constantly increasing efficiency and speed of elevators. Speeds of 900 ft. per min. are now operated. A recent development to increase space efficiency in high buildings, is the operation of two or more elevators in a single shaft, so synchronized that one elevator may be started and run as "express" for a certain number of floors before the car next below it starts. Needless to say the operation is interlocked by means of limit switches and kindred devices to prevent the cars from coming together.

General

Attention is called to the development of various types of apparatus which apply to transportation as well as to other forms of utilization of electricity as described in various technical committee reports. Included in this category are turbo-generators and other power plant facilities, motors, circuit breakers, insulators, transformers, lightning arresters, cables, relays, substations, etc. Many of these types of apparatus are applicable to transportation, only by accomplishing some more or less important modifications, and the attention of various technical committees has been called to special modifications of this kind.

Attention is called to the work which is being carried on under the auspices of the American Standards Association on Definitions of Electrical Terms (C-42) for which the A. I. E. E. is sponsor. To Subcommittee No. 6 is assigned the field of "Horizontal Transportation." It is hoped that when this very important subject is complete, and published, general use will be made of the definitions and that some confusion which now exists will thus be avoided.

Protective Devices

ANNUAL REPORT OF COMMITTEE ON PROTECTIVE DEVICES[*]

THE work of the Committee on Protective Devices during the past year was accomplished largely through subcommittees, which are listed below with their chairmen:

Relays, W. W. Edson; Oil Circuit Breakers, Switches and Fuses, L. F. Hickernell; Lightning Arresters, H. K. Sels; Fault Current Limiting Devices, H. B. Wood; Joint Interconnection Subcommittee,[†] F. C. Hanker.

The activities of the Protective Devices Committee may be divided into the following three classes:

1. Preparation of standards
2. Review of research and development
3. Fostering the preparation and presentation of papers.

GENERAL

During the year the work of the committee in cooperation with the National Electric Light Association in the preparation of a supplement to the Relay Handbook was completed.

Revised standards for lightning arresters have been prepared and issued in report form by the Standards Committee.

Progress has been made in the preparation of standards for fuses and revised standards for disconnecting, horn gap and knife switches. It was hoped that the standard for fuses could be sent to the Standards Committee this year, but due to difficulties in obtaining complete agreement as to the subject matter of this standard there has been some delay. These standards should be forwarded to the Standards Committee in the latter part of 1931.

The committee has maintained close contact with research and development relating particularly to lightning protection, high-speed oil circuit breakers, and stability of operation, which greatly facilitated its work in fostering the preparation of suitable papers relating to these subjects.

The work of the committee during the past year has emphasized more than ever the following points. First, the desirability of planning the presentation of papers sufficiently in advance so that they may be grouped for presentation in the most suitable manner. Second, the necessity, if maximum advantage is to be realized from Institute sessions, of having papers available for reading sufficient time in advance of meetings to permit of well considered discussion. The importance of this latter point is so great that every effort should be made to see that it is carried out effectively.

On account of the fact that in a number of cases other technical committees of the Institute have a very definite interest in the application or use of devices coming under the jurisdiction of the Protective Devices Committee, very close coordination of activities is required. This is particularly true in matters relating to interconnection and stability of operation handled at the present time by the joint subcommittee having representatives from the Power Generation and Power Transmission and Distribution Committees, in addition to the Protective Devices Committee. It may be that there will be sufficient important matters which affect a number of committees to warrant selecting some method of handling them that will permit of direct effective action without the complication and delays that are bound to happen in coordinating work with several large committees.

RELAYS

Report of Subcommittee

Further development of high-voltage transmission and interconnection with rather severe requirements as to stability and continuity of service, have focused attention on the necessity of rapid clearing with extreme precision, and the development of the art of relay protection has advanced as a consequence. Relays have been developed including directional, balanced, and differential relays capable of operating in one-sixtieth of a second.

These are being tried out in service and their operation is being watched with much interest. Apparently, additional work should be done to simplify these relays and their mechanical construction details, so as to insure among other things high-speed operation under all conditions, and to prevent shifting of the balance point. Also, further development will apparently have to be gone ahead with to eliminate certain difficulties in the application of these relays to short line sections or to ground protection.

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[*] COMMITTEE ON PROTECTIVE DEVICES:

Raymond Bailey, Chairman,
J. E. Allen,
A. C. Cummins,
H. W. Drake,
W. S. Edsall,
W. W. Edson,
L. E. Frost,
E. E. George,
Herman Halperin,
F. C. Hanker,
E. A. Hester,
L. F. Hickernell,
Dr. M. G. Lloyd,
J. P. McKearin,
H. A. McLaughlin,
A. M. Rossman,
A. H. Schirmer,
H. K. Sels,
H. P. Sleeper,
E. R. Stauffacher,
H. R. Summerhayes,
E. M. Wood,
H. B. Wood.

[†] This is a joint subcommittee of the committee on Power Generation, Power Transmission and Distribution and the Protective Devices Committee.

The most important work of the subcommittee for the year is the completion of the revised edition of the Relay Handbook, in cooperation with the corresponding committee of the N. E. L. A.

The following papers, prepared under the auspices of this subcommittee, have been presented before the Institute:

Relay Developments on Southern California Edison System, E. R. Stauffacher, Southern California Edison Company.

Operating Experience with Reactance Type Distance Relays, E. E. George, the Tennessee Electric Power Company.

Protection of Three-Winding Power Transformers, R. E. Cordray, General Electric Company.

Fundamental Basis of Distance Relaying, W. A. Lewis, Westinghouse Elec. & Mfg. Company.

OIL CIRCUIT BREAKERS, SWITCHES, AND FUSES

Report of Subcommittee

A prominent feature of oil circuit breaker development is the number of large installations of metal-clad switchgear. Among these may be mentioned the installation of 33-kv. oil-filled gear on the system of the Public Service Company of Northern Illinois, the 13-kv. gum-filled gear at the Leaside Substation of the Hydro-Electric Power Commission, and air-filled gear on the system of the Jersey Central Power & Light Company.

Since last year's development of the deion circuit breaker, further results have followed the discovery of this method of arc extinction. With the addition of deion grids, ordinary oil circuit breakers have opened 3,500 amperes at 110,000 volts with 1.5 cycles of arcing; and 3,000 amperes at 200,000 volts with 3.5 cycles of arcing or less. Decreased arcing assures more satisfactory breaker performance, less deterioration of oil and contacts and lower maintenance. The stability of the whole power system is improved, since short circuits are more likely to be cleared before they can affect synchronous machines.

The deion oil-less breaker in the meanwhile has been developed for a greater range of ratings. At one extreme is a one million kva. 23 kv. circuit breaker which has undergone interrupting capacity tests including some shots as high as 800,000 kva. (It will be recalled that among last year's achievements were reported successful interruptions of short circuits in the order of 60,000 kva.) On the other extreme is the breaker (using 2.5-inch plates) which repeatedly interrupted 10,000 amperes at 600 volts alternating current. This small deion breaker shows great promise in a wide field of the moderate and smaller powers; such, perhaps, as industrial service.

Efforts to improve rating standards for oil circuit breakers continue.

Announcements by the manufacturers indicate healthy activity in the development of new forms of circuit interrupters, such as the oil-blast oil-circuit breakers, multiple break and others.

The following papers, prepared under the auspices of this subcommittee, have been presented before the Institute:

The Mechanical Performance of Oil Circuit Breakers, A. C. Schwager, Pacific Electric Mfg. Co.

Outdoor Switching Equipment at Northwest Station, W. F. Sims and C. G. Axell, Commonwealth Edison Co.

Magnitudes and Rates of Rise of Circuit Breaker Recovery Voltages, R. H. Park and W. F. Skeats, General Electric Co.

Trend in Development of Modern Circuit Interrupters, J. B. MacNeill, Westinghouse Elec. & Mfg. Co.

Oil Circuit Breaker Tests—Philo 1930; Aims, Set-Up and Results from a System and Operating Point of View, Philip Sporn and H. P. St. Clair, American Gas & Elec. Co.

The Oil-Blast Circuit Breaker, D. C. Prince and W. F. Skeats, General Electric Co.

Field Tests on Standard and Oil-Blast Explosion Chamber Oil Circuit Breakers, R. M. Spurck and H. E. Strang, General Electric Company.

LIGHTNING ARRESTERS

Report of Subcommittee

The Subcommittee is advised that studies of lightning and the effects of lightning were continued throughout the year by means of field investigations on transmission systems in several widely separated localities. The knowledge of the character and behavior of high-voltage surges originating from lightning on transmission lines was extended by the use of cathode-ray oscillographs at field stations located in Arkansas, Illinois, Michigan, New Jersey, Ohio, Pennsylvania, and West Virginia. In two cases, Michigan and New Jersey, the behavior of waves on transmission lines was studied in detail by the use of both portable cathode-ray oscillographs and impulse generators. Practically a continuous investigation was maintained also of the performance of lightning arresters, and many other associated phases of the lightning protection problem. About 3,000 oscillograms were taken which have already proved valuable in the study of problems related to lightning protection.

Better coordination of records in the 1930 lightning investigations has indicated the growing importance of direct strokes. Records obtained on high-voltage lines tend to confirm the thought that overvoltage due to direct strokes are more important than those due to the induced effect from lightning strokes primarily on account of their greater magnitude.

Impulse tests made in the field tend to confirm the conclusion that best protection with lightning arresters is obtained when the arrester is located close to the equipment to be protected and the leads as short as possible with low ground resistance. If the arrester cannot be located close to the equipment and at the same time retain short leads, keeping the leads short appears to be the more important. Also, the arrester and equipment should be connected to the same ground but if this is not convenient, more attention must be given to the arrester ground to be sure that its resistance is as low as possible.

The highest voltage lightning arresters ever built were recently installed by the Hydro-Electric Power Commission of Ontario. Under emergency conditions of generator overspeed and abnormal line voltage, they will not be damaged by voltages as high as 268,400 volts. Normally, four of the twenty-two arrester units in each phase leg are short circuited by a high speed switch which opens automatically in less than half a second when waterwheel overspeed and overvoltage occurs. This is also the largest arrester installation for voltages over 200,000. One three-phase arrester is installed for the protection of each of four banks of transformers.

The commercial development of the porous block autovalve arrester has made available a new arrester which is considerably smaller and has much better performance characteristics than the earlier autovalve. The arrester is constructed in fewer porcelain-cased units with a totally enclosed gap structure which in the lower voltage sizes results in the complete arrester being housed in a single casing or two casings with gaps and elements separate. The protective action of the arrester is similar to the old one but it has practically no time lag in its operation and a low ratio of discharge voltage to normal voltage. A small and compact form of line arrester has been developed which can be applied to prevent the flashover of insulator strings. A number of installations of these line arresters has been under observation for the past two years in order to gather data on the effectiveness of such protection for transmission line insulators.

With the commercial development of thyrite, a new form of lightning arrester became available. The arrester is constructed in the form of self-contained units, it only being necessary for any application to mount an appropriate number of units one upon another. A gap structure has been provided in each unit so constructed that substantially no time lag occurs in the operation of the gap. This arrangement, coupled with the characteristics of the material, insures an arrester which has practically no time lag in its operation. A number of installations of these arresters has been made, the highest voltage arrester in service being of 230 kv. rating. Another form of thyrite arrester was developed which is incorporated in a string of suspension insulators and used to prevent the flashover of the insulator string for all but the most severe conditions.

A new protective device operating on a deion principle in a small bore tube for use in the prevention of insulator flashover by lightning has been developed in certain voltage ratings.

The revision of the proposed Standards for Lightning Arresters for alternating-current power circuits was completed and accepted by the Committee on Protective Devices for printing in report form. The subcommittee hopes that there will be widespread use of these standards in order that they may be put in final shape for adoption by the Institute. It is expected that development in the art of protection from lightning will probably make it necessary to revise these standards from time to time as additional technical information becomes available.

The work of the subcommittee indicates that the following matters should receive considerable attention in the future: (1) the determination of more representative test surges, (2) the development of tests to determine operating condition of arresters in service, (3) investigation of present operating practise on transmission and distribution systems relative to arrester installation, operation and performance as affecting suitable standards, and (4) the coordination of line and station type arrester application in the field with the activities of other committees interested in the grading of system insulation.

The following papers, prepared under the auspices of this subcommittee, have been presented before the Institute:

An Experimental Lightning Protector for Insulators, J. J. Torok, Westinghouse Elec. & Mfg. Co.

Field Tests on Thyrite Lightning Arresters Using Artificial Lightning of 1,500,000 Volts, K. B. McEachron and E. J. Wade, General Electric Company.

FAULT CURRENT LIMITING DEVICES

Report of Subcommittee

The reactor installations made during the year are characterized by high electrical ratings and greater physical size, particularly in bus-sectionalizing applications which seem to be on the increase.

Among the largest ever built in physical size is an application of 4,000-kva., 161-kv. bus sectionalizing reactors giving 10 per cent reactive drop when 120,000 kva. is transferred across the reactor.

Another outstanding installation from the standpoint of physical size consists of three 5,400-kva. oil-immersed reactors on the 110-kv. system of the Pacific Gas & Electric Co.

Noteworthy from the standpoint of electrical rating are eighteen bus-sectionalizing reactors rated 7,340 kva. giving a 16½ per cent reactive drop in a 133,000-kva., 27,600-volt circuit now on order.

Current-limiting reactors of the dry type installed in metal housings and rated 833 kva., 693 volts, 1,200 amperes, 60 cycles, were used to sectionalize a 24,000-volt bus. They introduce 5 per cent reactive drop between the sections when 50,000 kva. are being transferred. The housings are supported on insulators and are connected to a ground bus.

Bus-sectionalizing reactors were in some instances provided with disconnecting devices which automatically break the circuit when the reactor is removed from its operating location.

Representative opinion has been secured on the desirability of including in the new A. I. E. E. Standard for Fault Current Limiting Devices the material on reactors now in A. I. E. E. Standards No. 13 and also information on grounding transformers, generator neutral reactors, and Petersen coils. As yet no definite decision has been reached.

INTERCONNECTIONS

Report of Joint Subcommittee

The work of the Joint Interconnections Subcommittee has related almost entirely to the preparation of papers. A comprehensive paper on *Present Day Practise in Grounding of System Neutrals* was prepared by the subcommittee and presented at the Pittsburgh District Meeting.

A paper entitled *Impulse Test on Substations,* by Messrs. Brookes, Southgate, Roman, and Whitehead, was presented at the Winter Convention.

The following papers were presented at the Pittsburgh Meeting:

Committee Report on Present Day Grounding Practises, C. A. Powel, Chairman.

Reactance of Transmission Lines with Ground Return, J. E. Clem, General Electric Company.

Power System Voltages and Currents Under Fault Conditions, R. D. Evans and S. H. Wright, Westinghouse Elec. & Mfg. Company.

Simultaneous Faults and Six-Phase Transmission, Edith Clarke, General Electric Company.

Power System Voltages and Currents Under Fault Conditions, R. D. Evans and S. H. Wright, Westinghouse Elec. & Mfg. Co.

Series Resistance Method of Increasing Transient Stability Limit, R. C. Bergvall, Westinghouse Elec. & Mfg. Co.

Research

ANNUAL REPORT OF COMMITTEE ON RESEARCH[*]

DURING the year the Committee members have reviewed twenty-six papers and recommendations have been made to Headquarters for their disposition. Each paper has been reviewed by three or more members and outside experts. The Committee held one session at the Winter Convention at which eight of the approved papers were presented. Additional papers, obtained through the Committee on Research, are scheduled for the Summer Convention and several papers made available for district meetings. All business was carried on through correspondence as the only Committee meeting scheduled, at the Winter Convention, had to be abandoned because of conflicts.

The following topics are of sufficient importance to be called to the attention of the electrical engineering profession. The subjects reported have all been suggested by the Committee members, special assistance having been given by Messrs. W. G. Cady, V. Karapetoff, H. H. Race, D. W. Roper, T. Spooner, and J. B. Whitehead.

PHYSICS

In the field of physics there has been a number of theoretical and experimental accomplishments of some interest during the past year.

The knowledge of cosmic rays has been advanced somewhat with two schools of thought: certain investigators, as a result of certain experimental evidence, are convinced that cosmic rays are actually high velocity particles. However, Dr. Millikan, from intensity measurement of the cosmic rays in northern latitudes, feels quite certain that they are actually rays, since they are not affected by the earth's magnetic field. Dr. Millikan concludes that the cosmic rays have their origin not in the stars, but in interstellar space and that they are due to the building up of the commoner heavy elements from hydrogen, it being thoroughly established by spectroscopy that hydrogen is widely distributed through space. Several of the more common elements and also helium exists in interstellar space.

After seven years of intensive work, Dr. Paul Heyl of the Bureau of Standards has remeasured the constant of gravitation, or as the newspapers would put it, the weight of the earth. This figure is 6.670×10^{-8} c. g. s. units.

Eddington has developed a theory which makes possible the calculation of the ratio of masses of an electron and proton as well as the sizes of the electron and of the universe.

The generation of very short radio waves is possible by a number of means, among them the Barkhausen tube. This tube is a three electrode tube with suitable voltages applied to the grid and plate and provided with parallel Lecher wires. The frequency is dependent on the speed of the electrons as affected by the voltages and spacing of the electrodes and is independent of the external characteristics. Shuster has applied quantum mechanics to the problem of the Barkhausen tube and has calculated correctly the observed frequencies.

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As a result of the work of Grondahl it has been known for some years that copper oxide on copper had a photoelectric effect, making possible the generation of electric energy from sunlight. Dr. B. Lange of the Kaiser Wilhelm Institute for silicate investigation has obtained some interesting results with the copper oxide cell. According to newspaper reports he has, with the use of silver selenide, obtained similar results, but of one hundred or more times as much magnitude. However, for the generation of power from sunlight, the development is very far from being commercial owing to the high cost and low output.

MEDICINE AND PHYSIOLOGY

In the realm of medicine and physiology there has been a number of developments of interest to the electrical engineer. The recent paper on "Experiments on High Voltage Tubes," by Tuve, Hafstad, and Dahl of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, describes an X-ray tube, the voltage of which can be as high as 2,000 kilovolts. At 1,300 kilovolts the absorption coefficient, after filtering through one inch of lead is the same as that for the gamma rays from radium in equilibrium measured under the same conditions with the same instrument. This result has been attained by the so-called heat working of the pyrex glass. This high-voltage tube should serve as a new tool to the medical profession.

For the treatment of cancer there has been developed by Dr. W. D. Coolidge a 900,000-volt X-ray tube to be installed in the New York Memorial Hospital.

It is well known that fever assists in destroying certain disease germs. It is possible, by the use of high frequency electrostatic fields, to produce artificial fever, thus assisting nature. Considerable success has been obtained by this method during the past year.

Dr. George Sperti of the University of Cincinnati has succeeded in using selected regions in the ultraviolet spectrum for the irradiation of foods; for example, he has been able to create Vitamin D in milk without spoiling the taste.

Dr. H. C. Rentschler has developed a method for measuring ultraviolet radiation by the use of a suitably designed photocell and a condenser. The condenser is charged slowly through the photocell and discharges through a counter at a rate dependent upon the ultraviolet radiation received by the photocell.

DIELECTRICS

Considerable progress has been made in insulation and dielectric research during the past year. Much work is being done to improve the processing in the manufacture of high-voltage cable insulation and also to detect a faulty impregnated cable before it goes into service. At Johns Hopkins University the value of thorough drying by the use of vacuum and air pressure during impregnation and the use of gas free oils have been studied further. To detect poor insulation, research workers of the University of Illinois are measuring high frequency discharges which constitute internal ionization.

Studies on the oils themselves are under way at the Detroit Edison Company, Cornell University, and the Brooklyn Edison Company, with special emphasis on the life characteristics and products of such oils under electrical stress, particularly ionic and electronic bombardment. At the Detroit Edison Company, it has been found that by bombardment of the oil vapors in a vacuum, the composition of the gas produced varies from one hydrocarbon to another and is quite complex, but consists roughly of 50 per cent hydrogen and 50 per cent unsaturated hydrocarbons. Liquids and wax-like solids are also produced. The solid formed is a duplicate of the compound "X" found in cables which have been in service. The formation of this substance in cables indicates internal corona. Five normal paraffin hydrocarbons of simple chemical structure and of very high purity have been prepared at the Bureau of Standards and studies are being made of their electrical characteristics.

Further studies have been made of polar compounds in liquid dielectrics. The frequency-temperature-loss characteristics have been studied in a number of laboratories with most interesting results. In addition, the polar characteristics of certain commercial insulating liquids are being studied, particularly the change and polar characteristics during service. These fundamental studies should aid in a choice of better insulating oils.

At Johns Hopkins University correlation between d-c. absorption and a-c. dielectric loss has been verified for several oils, dried paper and impregnated paper consisting of the materials previously studied alone. The relatively high d-c. conductivity of oil obtained up to about one second after electrification was found to account for the a-c. losses. The electrical characteristics of the separate and combined materials of impregnated paper insulation have been studied. This is a very important step in the fundamental side of dielectric research.

Another field of investigation which is just getting under way is the use of X-rays to study the molecular structure of dielectrics. The work of Dr. Zwicky at the California Institute of Technology on mosaics and on sodium chloride crystals, and the work in Chicago by Dr. Bennett on the effect of an electric field on the arrangement of paraffin crystals are worthy of notice.

There have been numerous important and interesting engineering developments during the past year.

LIGHTNING RESEARCH

As the result of the investigations of natural and artificial lightning carried on at a number of field stations in various parts of the country, it has been pretty definitely established by the use of the cathode ray oscillograph that most outages and damage to transmission lines are the result of direct strokes rather than induced lightning. Two records during 1930 were obtained of crest values of 4,500 and 5,000 kv. The latter value was recorded at a distance of several miles from the stroke. At the place of flashover it is estimated that the potential was at least 10,000 kv. It has been concluded that a lightning stroke to a ground wire, if flashover does not take place, does not result in a surge over the line. By using proper precautions it is believed, as a result of these lightning investigations, that it will be possible to build transmission lines which will be practically immune from lightning.

There have been developed and placed on the market during the year, two new types of lightning arresters, namely the thyrite arrester by the General Electric Company and the new porous block autovalve arrester by the Westinghouse Elec. & Mfg. Co. These arresters have characteristics which are considerably superior to their predecessors.

The commercial development and application of new types of discharge tubes have been very active recently. It seems evident that these devices are going to occupy a very large place in the control and conversion of power.

RADIO

In connection with radio there have been developed and put into commercial operation, 200 kw. transmitting tubes for broadcast stations.

Mercury-glass three-phase rectifiers have been developed to supply plate current for these high power radio tubes. These rectifiers are rated at 10,000 volts and 30 amperes. Additional grid-controlled gaseous discharge tubes, namely, the Westinghouse grid glow tubes and the General Electric thyratrons which are similar in their characteristics, have been developed during the year, the larger sizes being able to handle 75 amperes at voltages up to 1,000 or even 2,000. A grid energy of ½ watt or less is required.

Many new applications for grid glow tubes have been made recently. Among them is the theater light dimmer system which is controlled by very small rheostats which regulate the voltage applied to the grids of the tubes. These tubes supply rectified alternating current to choke coils which are saturated by the pulsating current, thus changing the inductance and controlling the lights. The small control wires can be led to any desired location, thus concentrating the control and simplifying the operation of the system. There are no moving parts and contacts, except for the small control rheostats. A very great advantage of this type of control is that the whole lighting program for the evening may be preset.

MISCELLANEOUS

A new stroboscope called a stroboglow has been developed, which illuminates a moving object for a period of only 3/10 of a microsecond or less. This interval is so short that an object moving at seven miles a minute appears to be perfectly stationary with no appreciable blur. No moving parts are necessary and no connection between the stroboglow and the moving object is required. The instrument is calibrated for frequency and may be used to determine the speed of rotation of the illuminated object.

A very small tube rectifier has been developed, rated at 3/10 of an ampere and 5,000 volts. This rectifier is 4½ in. long and 1¼ in. in diameter. It can be operated satisfactorily up to 10,000 volts and under special conditions, has been carried as high as 30,000 volts. These tubes are particularly suited for airplane radio transmitters.

A new oscilloscope with a linear time axis has been developed which employs a new type of cathode ray tube for its essential element. This oscilloscope has the advantage over previous types in that it has a larger field and the illumination is very much greater, making it possible to observe recurrent phenomena in a well lighted room. Non-recurrent phenomena lasting for a few microseconds, can also be observed readily for qualitative results. For recurrent phenomena the cathode beam may be synchronized so that the image appears stationary.

An automatic traffic control system has been developed and put into experimental use on main highways, using a beam of light crossing the side streets. When a car or other vehicle approaches the main highway on the side street, the beam is intercepted, thus causing a photocell to act giving the minor street the green light.

There has been developed in Germany another application of the light sensitive devices for the purpose of stopping railroad trains. Light from the headlight of the locomotive is reflected from a mirror on the semaphore and returns to photocells on the locomotive, which when illuminated operate the automatic stop mechanism.

There has recently come into general use in this country the electric photo-flash lamp which was developed in Germany and is used as a substitute for flash-light powder. The bulb contains a quantity of aluminum foil in an atmosphere of oxygen. A small filament, when heated electrically, causes the aluminum foil and oxygen to combine with an intense illumination. The elimination of noise and smoke is greatly appreciated by the average audience.

Studies and applications of piezo electric quartz crystals have been continued at Wesleyan University. By means of the cathode ray oscillograph, the rate of dying away of the oscillations of these crystal resonators has been studied. It has been found that a 600-kilocycle crystal started vibrating and left to itself, makes 60,000 vibrations before its amplitude falls to 1 per cent of its initial value. Various types of mountings for the crystals as well as the effect of the shape, cut and material of the crystal itself are being studied. A determination of the viscosity of quartz as a function of frequency is yielded by the above measurements. The coefficient of viscosity or quartz is approximately five at 600 kilocycles as contrasted with 500 for aluminum at 60 kilocycles and with values of the order of 10^8 ordinarily quoted for the low-frequency viscosities of metals.

A very accurate clock developed by the Bell Telephone Laboratories was exhibited at Cleveland last December, which is unique in that it is controlled electrically by a spherical quartz crystal.

The Stevens Institute of Technology reports the development of a clock which is automatically corrected by the standard radio time signals.

The limitations and advantages of commutation and current collection in hydrogen have been determined by laboratory and commercial experiments. In general, in the hydrogen atmosphere there results a lower contact drop. Satisfactory operation and long life are obtained if sparking is kept low. If appreciable sparking is present the humidity must be kept low.

The application of the helical groove to slip rings and commutators has been developed and applied commercially. Under severe conditions of commutation and current collection this apparently reduces brush wear and improves the electrical operation by reducing the formation of local hot spots; also better distribution of current between parallel brushes results.

A sample of commercial hipernik (a 50 per cent nickel-iron alloy) has been obtained having a maximum permeability of 167,000. Test samples from other castings have given as high as 13,000 for initial permeability and upwards of 400,000 for maximum.

Work during the past year on the fundamental nature of arcs and their extinction has given a greater insight into the problem of circuit interruption and is having a very definite effect on the design of circuit breakers.

There has been developed a non-destructive magnetic weld test meter for use with butt welds, which shows some promise commercially. For a given type of weld and a definite kind of steel, comparative results on welds are quite reliable.

At the Naval Research Laboratories interesting work has been done using the radiographic method for detecting imperfections in large steel forgings. Ordinary X-rays can penetrate only three or four inches of steel, but by the use of radium it has been possible to obtain photographs through twelve inches of steel. The radium has the advantage that it can readily be transported to the piece to be inspected and requires no complicated auxiliary equipment. If thick pieces of steel are to be photographed, however, either a long time must be used or a considerable quantity of radium or radium emanation must be available.

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